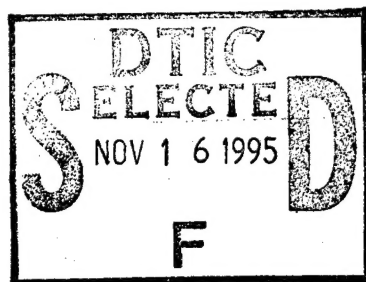


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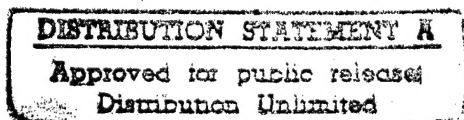
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CONCRETE-POLYMER MATERIALS

Final Report

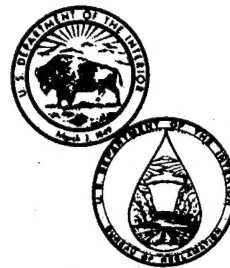
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16. ABSTRACT The Bureau of Reclamation and Brookhaven National Laboratory conducted a joint research program on development of concrete-polymer materials under the sponsorship of the then U.S. Atomic Energy Commission, the then Office of Saline Water, and the Bureau of Reclamation. The program began in 1967 and continued to June 1973. Five topical reports have been published on the work performed through June 1972. Test results presented were conducted at the Bureau during the final year of the cooperative program, and include: (1) work on monomer and composites surveys, (2) process technology development for PIC (polymer-impregnated concrete), (3) test results on PIC at ambient and elevated temperatures, (4) examination of PIC after exposure to brine at elevated temperatures, (5) nondestructive testing of PIC, and (6) a brief summary of applications development. The purpose of this report is to record final data from the testing program. Detailed analyses of these data are not included.		
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CONCRETE-POLYMER MATERIALS

Final Report

(USBR-BNL-AEC-OSW Cooperative Program)

by

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August 1976

Concrete and Structural Branch
Division of General Research
Engineering and Research Center
Denver, Colorado



UNITED STATES DEPARTMENT OF THE INTERIOR

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This is the final report on the cooperative program for the development of concrete-polymer materials conducted jointly by the Bureau of Reclamation and Brookhaven National Laboratory under the sponsorship of the then U. S. Atomic Energy Commission, the then Office of Saline Water, and the Bureau of Reclamation of the U.S. Department of the Interior. The final stages of the program were planned under the direction of G. J. Rotariu of the U. S. Atomic Energy Commission, E. J. Meeks of the Office of Saline Water, B. Manowitz and M. Steinberg of Brookhaven National Laboratory, and H. J. Cohan of the Bureau of Reclamation.

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ABBREVIATIONS

Technical

AN	Acrylonitrile
cP	Centipoise
Cps	Cycles per second
C OF VAR.	Coefficient of variation
dB	Decibels
°C	Degrees Celsius
°F	Degrees Fahrenheit
DTA	Differential thermal analysis
EP-S	Epoxy-styrene
FA	Furfuryl alcohol
Hz	Hertz
MMA	Methyl methacrylate
CS	Monochlorostyrene
PE	Polyester
PE-S	Polyester-styrene
PCC	Polymer-cement concrete
PC	Polymer concrete
PIC	Polymer-impregnated concrete
PMMA	Polymethyl methacrylate
R	Radiation-initiated polymerization
CP	Standard concrete mix used in concrete-polymer materials development program:

cement	5.5 sacks/yd ³ (7.2 sacks/m ³)
max. aggregate	3/4-inch (19-mm)
water/cement ratio	0.51
slump	3-inch (76-mm)
entrained air	6 percent
compressive strength	5,000 lb/in ² (34.5 MPa)

STD DEV	Standard deviation
S	Styrene
S-TMPTMA	Styrene-Trimethylolpropane trimethacrylate
T	Thermal-catalytic polymerization
TMPTMA	Trimethylolpropane trimethacrylate

Organizations

ACI	American Concrete Institute
ACPA	American Concrete Pipe Association
BNL	Brookhaven National Laboratory
ERDA	Energy Research and Development Administration
NBS	National Bureau of Standards, U. S. Department of Commerce
USBR	Bureau of Reclamation, U. S. Department of the Interior
WSU	Washington State University

1. INTRODUCTION

Research on concrete-polymer materials under sponsorship of the U.S. Atomic Energy Commission¹ and the Office of Saline Water² was initiated as a cooperative program in 1967 between the Department of Applied Science at BNL (Brookhaven National Laboratory) and the USBR (U.S. Department of Interior's Bureau of Reclamation). Five topical reports have been published on the work performed through June 1972 [1, 2, 3, 4, 5]³. These reports give extensive background, test results, and data analysis on each of the various major tasks in the program.

In February of 1973, the Bureau was advised by the program sponsors that due to curtailment of available funds, work on the cooperative program would be terminated in June 1973. This report presents results of tests performed during the final year of the program, and summarizes the final results of the work done only by the Bureau.

2. MONOMER SURVEY — POLYMER-CEMENT CONCRETE STUDIES

Investigators at WSU (Washington State University) conducted tests [6] to optimize the curing of FA (furfuryl alcohol) monomer in PCC (polymer-cement concrete). Based on test results, eighteen 3-inch (76.2-mm)⁴ diameter by 6-inch (152.4-mm) long test cylinders were prepared by WSU for testing at the Bureau.

The concrete mix for the test cylinders and the control cylinders contained:

Concrete mix	Percent by weight
Aggregate	
3/8 inch to 3/4 inch	27.4
No. 4 to 3/8 inch	18.3
No. 8 to No. 4	5.0

¹The Divisions of the then Atomic Energy Commission involved in this study are now a part of ERDA (Energy Research and Development Administration).

²The then OSW (Office of Saline Water) is now a part of the OWRT (Office of Water Resource Technology).

³Numbers in brackets refer to the Bibliography at the end of the report.

⁴Research work was done using English units and converted to SI metric in accordance with ASTM Designation E-380-76.

No. 16 to No. 8	5.0
No. 30 to No. 16	8.4
No. 50 to No. 30	8.1
No. 100 to No. 50	5.4
Minus No. 100	1.7

Type II portland cement	13.8
Water	6.9
Total	100.0

The PCC test cylinders were prepared using the above concrete mix with the addition of 5 percent FA (furfuryl alcohol) and 5 percent calcium chloride (percentages by weight of portland cement).

Test results are reported in tables 1 through 4. Compressive and tensile strengths of PCC and conventional control concrete cylinders are similar (table 1). An increased compressive strength for the cylinders which had been used to determine water absorption probably resulted from the oven-drying at 250°F (121°C).

Data in table 2 indicate that PCC has less water absorption and a slightly higher density than the standard concrete mix (CP).

The PCC cylinders exposed to 5 weight percent sulfuric acid (table 3) underwent less than half the weight loss of the CP-type concrete. The PCC cylinders showed poor durability when exposed to freeze-thaw exposure (table 4).

Although the acid resistance, strength, and physical properties data are perhaps somewhat encouraging, the freeze-thaw performance was disappointing. If the work were to continue, additional studies should be performed to fully evaluate the use of other catalysts, such as aniline hydrochloride with a lesser amount of calcium chloride.

3. PROCESS TECHNOLOGY DEVELOPMENT — CONCRETE COMPOSITION

Studies to determine the effect of concrete mix design variables on properties of PIC (polymer-impregnated concrete) were extended to include additional variables. Tables 5 through 8 report results of tests for compressive strength, tensile splitting strength, absorption, specific gravity, and polymer loadings for low-strength, no-fines, gap-graded, and CP-type concrete specimens.

Polymer loadings and compressive strengths of PIC specimens averaged 9.9 percent and 16,500 lb/in² (114

MPa) for the low-strength mix, 6.9 percent and 20,900 lb/in² (144 MPa) for the no-fines mix, 6.7 percent and 20,500 lb/in² (141 MPa) for the gap-graded mix, and 5.8 percent and 20,400 lb/in² (141 MPa) for the CP mix. All the low-strength mix specimens were inadvertently impregnated.

In addition, a series of 3- by 6-inch (76- by 152-mm) cylinders and 1- by 1- by 10-inch (25- by 25- by 254-mm) prisms were prepared using a highly alkali-silica-reactive aggregate. Specimens were impregnated with MMA (methyl methacrylate) at various ages after casting to study effects of impregnation on alkali reaction. Expansion of unimpregnated and MMA-impregnated bars is given in table 9. The impregnation of the bars apparently curtails the alkali-aggregate reaction.

The unimpregnated bars show a fairly rapid rate of expansion, which is normal for this type of material. The impregnated bars show a similar rate of expansion up to the time of impregnation. At the time of impregnation the bars show a large contraction, which is due to overdrying. After impregnation, the bars show a small rate of expansion; it is not known at this time if this expansion is solely due to moisture absorption or if it is due in part to a greatly reduced rate of alkali-aggregate reaction. The 3- by 6-inch (76- by 152-mm) cylinders are being stored under conditions of 100 percent relative humidity and are planned to be used at a later time to study effects of alkali-aggregate reaction and impregnation on compressive strength.

4. TEST RESULTS ON POLYMER-IMPREGNATED CONCRETE

4.1 POLYMER-IMPREGNATED CONCRETE FOR AMBIENT TEMPERATURE APPLICATIONS

4.1.1 Structural Properties

4.1.1.1 Flexure.— A computer program was written to analyze/simplify the data and tabulate results of flexure tests. Data were analyzed for flexure tests on ten 3- by 5- by 54-inch (76- by 127- by 1372-mm) beams reinforced with one No. 4 bar, 0.75 inch (19 mm) from the bottom surface. A schematic diagram of the test setup is shown on figure 1.

Five beams were unimpregnated control specimens and five were impregnated with (10-90) polyester-styrene. Tests were run at room temperature. Test results shown in tables 10 and 11, indicate little difference between control and PIC specimens.

Early tests of MMA and (60-40) styrene-TMPTMA (trimethylol-propane trimethacrylate) impregnated beams yielded similar results. As reported in the Fifth Topical Report [5], calculations indicate the beams to be underreinforced. Consequently, the test results were more a function of the reinforcing steel than of the concrete. This is also true for the test results shown in tables 10 and 11.

Flexure data were prepared from the tests run during the last reporting period on unreinforced 3- by 3- by 16-inch (76- by 76- by 406-mm) bars. Five bars were impregnated with (10-90) polyester-styrene, and five bars were unimpregnated control specimens. Examination of the results in tables 12 and 13 show that the strength parameters of the PIC bars are about 2.62 times greater than those of plain concrete. Also, the flexural modulus of elasticity is greater for PIC, but only by a factor of about 1.14. It is noted also that coefficient of variation is much higher for the PIC bars than for the control bars. During testing it was noted and can be seen from the polymer loading in table 11 that specimen No. 72.144.5 was not fully impregnated. The low strength of this specimen is the principal reason for the high coefficient of variation exhibited by the PIC specimens.

4.1.1.2 Shear.— Five control and five (10-90) polyester-styrene impregnated 3- by 5- by 54-inch (76- by 127- by 1372-mm) beams were tested in shear. Each beam was reinforced with two No. 4 bars. One bar was placed 0.75 in. (19 mm) from the top surface and the other 0.75 in. (19 mm) from the bottom surface. Beams were loaded as shown on figure 1, which is a change from the past load tests of this size beam. In past tests, a flexural rather than a shear-type failure was obtained on PIC specimens. For this reason, the spacing between the top and bottom loads on the specimen at the center was changed from 10 inches (254 mm) to 5 inches (127 mm). Tests on all PIC and control beams, currently being reported upon, failed in shear.

Test results are shown in table 14. Shear values obtained for PIC specimens are approximately 80 percent greater than those of the control specimens. Computations were made to determine the nominal shear stress permissible by the ACI (American Concrete Institute) 318-71 Code. Test values of nominal shear stress were about 4.7 times greater for PIC specimens and 3.7 times greater for control specimens than those allowed for design by the code.

4.1.1.3 CP Test Series.— *Strength After Longtime Loading.* Concretes impregnated with four different

monomers and unimpregnated concretes that have been under continuous 800 lb/in² (5.5 MPa) compressive load for 3 to 4-1/2 years were removed from creep tests. Strength determinations on these specimens reveal that the longtime load condition has no apparent effect on strength (table 15). Strengths of control specimens that have never been under load are essentially the same as the cylinders that were under creep tests for several years.

4.1.2 Durability Properties

4.1.2.1 Full Impregnation

(a) CP Test Series

● *Resistance to sulfate attack.* — Test results on impregnated concrete specimens are reported in table 16.

● *Resistance to freezing and thawing.* — Test results on impregnated concrete specimens are given in table 17. The MMA specimen (specimen No. BNL-1-3) has been in test longer than any other specimen and shows a weight loss of 2 percent after 14,690 cycles (about 5-2/3 years). The MMA-TMPTMA specimen (CP-4B-3B) remaining in the test has a weight loss of 8 percent after 11,130 cycles. The polyester-styrene specimen (CP-7-3B) has a weight loss of 3.5 percent after 4,210 cycles.

● *Resistance to 5 percent sulfuric acid.* — After 459 days, most of the impregnated concretes have lost over 25 percent of their original weight in the test, indicating that resistance of these materials is about 2.3 times greater than the unimpregnated material. The unimpregnated control concretes have previously reached 25 percent weight loss at less than 200 days (table 18). Compressive strengths of the impregnated cylinders, after failure in the sulfuric acid solution, averaged over 5,000 lb/in² (34.5 MPa).

● *Strength loss after exposure to freezing and thawing and to acid.* — A series of tests were performed to develop additional information on the durability of PIC versus unimpregnated concrete and to investigate the feasibility of establishing a quicker cut-off date on running the tests, particularly in view of the time problem in testing various PIC formulations for improvements in durability. The freeze-thaw test and resistance to 5 percent sulfuric acid were selected as the basic durability tests, and the properties measured were: (1) loss in compressive and tensile strength, (2) dynamic modulus of elasticity (resonant frequency), (3) ultrasonic pulse velocity, (4) length change, and (5) weight loss.

All durability test specimens were placed in water for 1 week. Initial weight, length, pulse velocity, and dynamic modulus of elasticity measurements were made after the 1-week soaking in water. All measurements during testing were made with moist surface-dry specimens. Initial strength measurements were made with air-dry specimens. In the calculation of test data, no compensation was made for weight loss or reduction in section, and the reported results should be considered as apparent values. Test results are given in table 19 to 30.

The test results indicate that weight loss, compressive strength, pulse velocity, and dynamic modulus of elasticity measurements have some merit (along with some inherent limitations) in evaluating durability.

PIC shows excellent resistance to freezing and thawing compared to conventional concrete. After 1,300 cycles, PIC specimens undergo a slight weight loss of less than 1 percent and retain a compressive strength of about 19,000 lb/in² (131 MPa). Although the PIC samples appear to be in good condition after 1,300 cycles, it is evident that some deterioration or microfracturing has occurred. The deterioration of PIC appears to be best indicated by the moderate losses in compressive strength, pulse velocity, dynamic modulus of elasticity, and to a lesser extent by weight loss. The deterioration of unimpregnated concrete appears to be best indicated by compressive strength, pulse velocity, dynamic modulus of elasticity, and to a lesser extent by weight loss. Since the tensile splitting tests did not show a strength loss, this test does not appear to be a good indication of deterioration for the freeze-thaw test. Length change measurements likewise do not appear a suitable means for evaluating the test.

The PIC specimens showed good resistance to 5 percent sulfuric acid compared to unimpregnated concrete. After 170 days' exposure, PIC specimens had a compressive strength of about 12,000 lb/in² (82.7 MPa) and a weight loss of 3 to 6 percent. The testing of PIC presents some problems in evaluation, thus requiring more adequate evaluation criteria. Acid attack is best indicated by visual examination to determine the onset of attack and the progress of the attack in the initial stages. As the attack progresses, the best criteria appears to be a compressive strength test. This could be accompanied by sectioning of the specimens and visual examination for indications of acid attack in the interior of the specimen. Weight loss of PIC in exposure to acid is likely to be misleading as reaction products tend to be retained in the specimen. Acid resistance of unimpregnated concrete is best indicated by weight loss and compressive strength. Pulse velocity appears to be potentially useful in evaluation of acid exposure on PIC.

and unimpregnated concrete, provided that a suitable method is used to overcome the effects of acid on the ends of the specimens.

4.1.2.2 Partial Impregnation. — Partially impregnated concrete is under investigation as a less costly alternative to fully impregnated concrete in applications where durability rather than high strength is required. The monomer should effectively seal the surface and penetrate enough to prevent separation of the impregnated layer and premature failure. In these test series, viscous monomer systems and impregnation under pressure were used. Viscous monomer systems are used because: (1) penetration depths are more easily controlled, (2) voids in the penetrated portion remain filled, and (3) monomer losses due to evaporation and drainage during the time between impregnation and complete polymerization are lower.

The first series of partial impregnation tests used epoxy- and polyester-styrene monomer mixtures. The specimens were impregnated to depths of 1/16, 1/8, and 1/4 inch (1.6, 3.2, and 6.4 mm). Difficulties were encountered in obtaining uniform penetration within the desired closely spaced depths. Work to develop better systems for controlling penetration continues with a second series of tests using polyester-styrene monomer and PMMA [poly(methyl methacrylate)] prepolymer. A third series of tests was started to evaluate the effects that the use of high-pressure steam-cured concrete and high air-entrained concrete might have on the durability of partially impregnated concrete. The third test series originally included lightweight concrete specimens using expanded shale aggregate; however, since these specimens all contained cracks, they were not tested. The cracks evidently occurred during or subsequent to impregnation and polymerization. The cause of the cracks is not known. Two typical specimens are shown on figure 2.

● **Resistance to freezing and thawing.** —

The first test series are complete and the results reported in the Fourth Topical Report [4]. Second test series results are given in table 31. Freeze-thaw tests were not scheduled on third test series specimens.

● **Resistance to sulfate attack.** —

Test results on first and second test series specimens are given in tables 32 and 33. Sulfate resistance tests were not conducted on third test series specimens.

● **Resistance to acid attack.** —

First test series results on resistance to 15 percent hydrochloric acid were reported in the Fifth Topical Report [5]. Test results on resistance to 5 percent sulfuric acid for second and third test series specimens are reported in tables 34, 35, and 36.

4.2 POLYMER-IMPREGNATED CONCRETE FOR DESALTING APPLICATIONS AT TEMPERATURES UP TO 290°F (143°C)

4.2.1 Structural and Physical Properties

4.2.1.1 Compressive Stress-Strain. — Eighty 6- by 12-in (152- x 305-mm) cylinders were tested in compression at various temperatures after 6 month's exposure (tables 37 through 44). Forty specimens were impregnated with (70-30) MMA-TMPTMA, and forty were unimpregnated. Ten of each type were tested at each of the four temperatures. The test temperatures were -10°F (-23°C), 70°F (21°C), 250°F (121°C), and 290°F (143°C). As shown in tables 37 through 44, no significant difference is noticeable in the impregnated specimens at -10°F (-23°C) and 70°F (21°C). However, both the ultimate strength and modulus of elasticity indicate a significant reduction at the higher temperatures. Ultimate strength of plain concrete does not appear to be affected as much by high temperature as polymer-impregnated concrete. Modulus of elasticity does decrease at the higher temperatures. Compressive strength tests were also performed on unimpregnated (60-40) styrene-TMPTMA impregnated, and (70-30) MMA-TMPTMA impregnated concrete following storage for 14 to 17 months at -10°F (-23°C). Results are reported in table 45. Other long-term tests at different temperatures were not performed because the program was terminated.

At the time the specimens were placed in their respective environments, control specimens were tested at the same temperatures. They were maintained in the environment about 24 hours or just long enough to be sure they were at the desired temperature. The average values obtained in the 24-hour and the 6-month tests are given in table 46. Results indicate that the length of exposure at least up to 6 months does not greatly change the ultimate strength or the modulus of elasticity.

4.2.1.2 Compressive Strength From -10°F (-23°C) to 290°F (143°C). — Twenty-five unimpregnated 6- by 12-inch (152- by 305-mm) cylinders were tested at four temperatures to serve as controls for long-term tests of (70-30) MMA-TMPTMA and (60-40) styrene-TMPTMA impregnated specimens. Ten were tested at -10°F (-23°C) and five each at 70°F (21°C), 250°F (121°C), and 290°F (143°C), see tables 47 through 50. The highest strength was obtained at -10°F (-23°C) and was about 39 percent greater than the lowest strength at 70°F (21°C). It was unexpected to find the lowest strength at 70°F (21°C). However, the strengths at all temperatures except -10°F (-23°C) were virtually the same. At the elevated temperatures, both modulus of elasticity and Poisson's ratio were significantly lower than at either -10°F (-23°C) or 70°F (21°C).

4.2.1.3 Tensile Splitting Strength From -10°F (-23°C) to 290°F (143°C).—Data were reduced for tensile splitting tests performed on twenty-five 6- by 12-inch (152- by 305-mm) cylinders impregnated with (60-40) styrene-TMPTMA. Test results are presented in tables 51 through 54. Ten specimens were tested at -10°F (-23°C), and five each were tested at 70°F (21°C), 250°F (121°C), and 290°F (143°C). Results indicate no significant difference for the lower three temperatures. However, a significant loss of strength is apparent at the 290°F (143°C) temperature.

4.2.2 Resistance to Hot Brine and Vapor

Styrene-TMPTMA and MMA-TMPTMA PIC specimens were tested after exposure to brine, vapor, and the brine/vapor interface at temperatures of 250°F (121°C) and 290°F (143°C). There was about a 5-month delay between the time the test loops were shut down until the tests were begun.

MMA-TMPTMA specimens exposed to brine and vapor at 290°F (143°C) for 1 year were found to be highly deteriorated and tests for compressive strength were not possible. The other specimens were apparently in good condition. Styrene-TMPTMA and MMA-TMPTMA specimens had about the same compressive strength, 11,500 lb/in² (79.2 MPa) after 1 year exposure to brine and vapor at 250°F (121°C). Tables 55 and 56 give test results on compressive strength, pulse velocity, unit weight, and specific gravity; tables 57 and 58 give results on resonant frequency, weight change, and length change; and tables 59 and 60 give results on flexural strength tests.

5. FUNDAMENTAL STUDIES

PIC specimens were examined after exposure to brine and vapor at 250°F (121°C) and 290°F (143°C). The results of the examination are given in the appendix.

6. QUALITY CONTROL — NONDESTRUCTIVE TESTS

A variety of nondestructive test methods have been studied for use on PIC. These methods include ultrasonic pulse velocity, ultrasonic resonant frequency, acoustic impact, acoustic emission, neutron radiography, gamma ray and neutron transmission, infrared radiography, microwave transmission, dielectric and electrical resistivity, and impact hammer. Absorption, permeability, specific gravity, and length change measurements might

also be included. Although there is sufficient theoretical basis for each of the various methods, the heterogeneous nature of concrete makes the practical application of any one or a combination of methods extremely difficult. These methods work best with a homogeneous material in which a flaw, defect, or change in composition or uniformity can be readily detected. Concrete consists of a random mixture of aggregate particles of greatly varying size and shape and derived from a variety of different rock types, each of which may range from hard and dense to weathered, porous, and fractured; cement paste which invariably contains fractures; and variable amounts of moisture. The use of a non-destructive test method requires extensive calibration and standardization for a particular concrete mix. Even with careful concrete control practices, the variation between batches of the same mix may present some difficulties. The more practical approach appears to be in good process control to insure uniformity of treatment and testing of selected specimens to verify product quality.

6.1 ULTRASONIC PULSE VELOCITY

Ultrasonic pulse velocity has been extensively investigated for use with conventional concrete. Commercial instruments are readily available. The velocity measurements can detect variations in density and moisture content, the presence of fractures, and also the polymer in PIC, but the interpretation of the measurements is difficult because the velocity is affected by a number of these factors.

A series of tests was made on 3- by 6-inch (76- by 152-mm) cylinders to observe the effects of moisture content and polymer loading on pulse velocity. The results are shown on figure 3. The data show pulse velocity increases with increased moisture in conventional concrete and with increased polymer loading in PIC. The changes in pulse velocity in general look fairly uniform (with an apparently anomalous exception observed showing a high value of 14,600 ft/s (4450 m/s) for concrete containing 0.7 percent moisture).

Ultrasonic pulse velocity measurements were made on prestressed concrete bridge deck panels No. 9 and 10 before and after drying and after impregnation and polymerization. Panel No. 10 had lower pulse velocities at the undried, dried, and polymerized conditions than panel No. 9 or the 3- by 6-inch (76- by 152-mm) cylinders (fig. 4). According to the weight recorded for the panels, there does not appear to be a significant difference in density and no satisfactory explanation could be made for the lower pulse velocities recorded for

panel No. 10. A more comprehensive effort would be required to analyze the variation among the individual specimens and to interpret test results.

6.2 MICROWAVE TRANSMISSION

The NBS (National Bureau of Standards), Boulder, Colo., has an electromagnetic nondestructive test method under development. The apparatus is a microwave transmitter and receiver with a data display. In normal procedure, microwaves are transmitted through a medium and reflected back by interfaces or changes within the medium in a manner somewhat similar to the seismic reflection method used in geophysical exploration. In addition to the back reflection method, the test can also be conducted by direct transmission through the specimen by locating the receiver on the opposite side of the specimen. Microwave transmission is sensitive to abrupt changes in dielectric characteristics and under appropriate conditions can be used to detect layering, voids and cracks, areas of high moisture content, thickness of surface and subsurface layers, texture of surface layer, moisture content, packing density of subsurface layers, thickness of surface and subsurface layers, and buried objects.

The instrument operates over a range of frequencies from 0.1 to 10 GHz (gigahertz) and sweeps continuous wave band widths from 4000 to 8000 MHz (megahertz). The penetration of the material is dependent upon dielectric properties and decreases as the frequency increases. In the normal mode of operation, the analysis of data is based upon wave attenuation.

Samples of water-saturated, air-dry (50 percent relative humidity), oven-dried, and PIC were tested. Test results are shown on figure 5. The test is very sensitive to moisture and shows a small but detectable difference between oven-dried and PIC. It should be noted that the ultrasonic pulse velocity and the microwaves show good sensitivity to the presence of moisture. The ultrasonic method shows roughly the same effect for the presence of polymer as for the presence of moisture; whereas, the microwave method shows only a minor effect from the presence of polymer.

The microwave technique is theoretically sound. The electronic components of the apparatus are commercially available, and basic developmental work has been done by NBS. However, there would be significant costs to develop the technique for concrete applications. These expenses include assembling portable and compact equipment and performing the necessary standardization and calibration work.

6.3 NEUTRON AND GAMMA RAY

Neutron and gamma ray measurements were made with a commercial nuclear moisture and density determination apparatus. Moisture determination is made from neutron measurements, and density determination from gamma ray measurements. The instrument was operated in a back reflection mode on a 3-ft by 3-ft by 4-inch (914- by 914- by 102-mm) concrete slab at two locations on the slab. Measurements were made with the concrete in air-dried and oven-dried conditions and after surface impregnation and polymerization. The polymer was located at the top surface of the slab, extending into the slab to a depth of approximately 1 inch (25 mm). These measurements are considered very rough and should be considered as only indicative of the test method capability rather than as a precise experiment. The main problems encountered in performing the experiment were:

- The transmitter and receiver were placed directly on the concrete surface. The concrete surface, being relatively rough, quite likely produced some loss of radiation from scattering and a small but undetermined error in readings. This loss could possibly be minimized by supporting the transmitter and receiver a fixed distance from the concrete surface or by changing the mode of operation to direct transmission through the specimen.

- Sometime after the experiment, a defect in an electronic component of the instrument was detected. This may or may not have introduced a source of error in the measurements.

Results of the experiment are shown in table 61. The neutron moisture determinations and gamma ray density determinations show some relationship to the actual condition of the concrete. The calculated values for density and moisture or polymer content are lower than the actual values and probably represent errors in measurement and calibration. The indicated moisture content from neutron measurements for oven-dried concrete is attributed to water of hydration in the portland cement which is not free water.

6.4 COMMENTS ON OTHER NONDESTRUCTIVE TESTS

6.4.1 Ultrasonic Resonant Frequency. Standard procedure (ASTM Designation C 215-60) for evaluation of the freeze-thaw test is used to determine dynamic modulus of elasticity. Results are customarily expressed as the square of the resonant frequency or converted to

modulus of elasticity. Polymer impregnation produces an increase in resonant frequency squared of some 30 percent to 60 percent. This method is considered more applicable for durability tests than for determination of product quality or correlation with structural properties.

6.4.2 Acoustic Impact. This is a relatively new test. Only one company is known to manufacture a specific device for this type of test. The test was originally developed for detecting fractures in rivets and fasteners. The test consists of mechanically striking the test specimen and measuring the time for the shock wave to dampen a predetermined value. A BNL study [5] indicated that the test showed dampening of transmitted signals correlated with polymer loading, but the test showed more promise when used to determine vibration frequencies. This test procedure showed excellent correlation with measurements conducted according to ASTM Designation C 215-60. It was observed that the presence of moisture had no effect on resonant frequency and that polymer impregnation increased the square of resonant frequency by about 40 percent.

6.4.3 Neutron Radiography. Neutron radiography is similar to neutron moisture determination methods, being based upon the selective attenuation of thermal neutrons by hydrogen, except a picture is the end product instead of a dial reading. A BNL study [3] showed that neutron radiographs of PIC are difficult to interpret due to overlapping and extensive shadows to the aggregate particles. The method is potentially useful for observing very large variations in polymer loading within a sample; however, the equipment is expensive and further application of this method is not anticipated.

6.4.4 Infrared Radiography. A device is on the market which produces an image derived from the infrared radiation emitted by an object. The apparatus is fairly sensitive and can detect variations of about 1.8°F (1°C) in surface temperature. A brief test with this apparatus indicated that under ideal conditions polymer-impregnated zones in a concrete specimen could be distinguished from unimpregnated zones; however, unequal heating or cooling of the specimen can easily mask the effects of the polymer.

6.4.5 Acoustic Emission. This is a method in which a transducer "hears" subaudible noise emitted when a material is stressed. The rate and amplitude of the stress waves may be analyzed to determine if a structure is nearing failure. Grids of transducers are used to

locate flaws. This method requires extensive experience with a particular material before it can be used as an analytical tool.

6.4.6 Electrical Resistivity and Dielectric Constant. A limited study was made to investigate the suitability of electrical resistivity and dielectric constant measurements as a nondestructive test method [4,5]. However, the dielectric constant and electrical resistivity could not be related to polymer loading in test specimens. A test of nine fully impregnated concrete specimens with polymer loadings of 6.7 to 8.0 weight percent had dielectric constants ranging from 6.56 to 7.23 and resistivities ranging from 46.9 to 69.0 megohm-metres. A set of partially impregnated specimens with polymer loadings of 3.9 to 5.2 weight percent had dielectric constants from 6.87 to 7.18 and resistivities of 50.1 to 56.9 megohm-metres which are within the range of values observed for the fully impregnated specimens.

6.4.7 Impact Hammer. The impact hammer is a commercially available device designed primarily for field testing of concrete. The instrument measures hardness by impacting a steel rod against the test surface and observing the rebound. The rebound number is considered indicative of quality; the higher the rebound number, the higher the quality. The instrument has been used to obtain information on the extent of curing in concrete and to delineate sound from unsound zones in concrete structures. Attempts have been made to correlate rebound number with strength, but have not been successful except possibly under carefully controlled experiments with a known concrete mix. The impact hammer tests the surface of the concrete to a depth of about 1 to 2 inches (25 to 51 mm) and is not sensitive to the condition of the concrete in the interior of the specimen. Rebound readings are influenced by surface conditions, orientation of the hammer, coarse aggregate particles immediately below the hammer, size of the specimen, and the restraint placed on the specimen to hold it in place, all of which are not related to quality or strength of the concrete. Impact hammer tests generally show PIC to give a rebound number about 20 to 65 percent greater than unimpregnated concrete [3].

7. APPLICATIONS DEVELOPMENT

7.1 PIPE APPLICATIONS

7.1.1 Joint USBR/BNL/ACPA Program. A report covering work conducted under the joint USBR/BNL/ACPA (American Concrete Pipe Association) research program has been published [7].

7.1.2 PIC Draintile

7.1.2.1 Resistance to Sulfate Attack.—Westlands PIC Draintile.—Sodium sulfate tests on concrete draintile have reached 1,092 days' exposure. Expansion results at this age still indicate that the epoxy-styrene-impregnated concrete is much more resistant in the accelerated test, but about the same in resistance as the unimpregnated tile in the 10 percent sulfate solution, table 62.

7.2 PRECAST TUNNEL SUPPORTS AND LININGS

A report covering work conducted under the joint Bureau of Reclamation/Bureau of Mines/Department of Transportation research program has been published [8].

8. SUMMARY AND CONCLUSIONS

Test results from the last year of the testing program are briefly summarized as follows:

- Studies of the effect of concrete mix design variables on properties of PIC show compressive strengths of PIC specimens averaged 16,500 lb/in² (114 MPa) for a low-strength mix, 20,900 lb/in² (144 MPa) for a no-fines mix, 20,500 lb/in² (141 MPa) for a gap-graded mix, and 20,400 lb/in² (141 MPa) for the standard CP mix.

- A preliminary study with concrete and mortar specimens made with a highly alkali-reactive aggregate indicated that polymer impregnation curtails alkali-aggregate reaction.

- Flexure tests were conducted on reinforced and nonreinforced (10-90) polyester-styrene PIC. Calculations showed the reinforced beams were underreinforced and the test results were more a function of the reinforcing steel than the concrete. Flexure tests on nonreinforced beams indicated PIC specimens were 2.6 times stronger than plain concrete.

- Shear tests performed on reinforced beams showed that shear strength of PIC is about 80 percent greater than that of unimpregnated concrete.

- Compressive strength tests on PIC specimens that have been under 800 lb/in² (5.5 MPa) compressive load for 3 to 4-1/4 years showed that the long-term load conditions had no apparent effect on strength.

- Long-term durability tests on PIC specimens were continued. Length of exposures ranged upwards to

2,106 days in the accelerated sulfate attack test, 459 days immersion in 5 percent sulfuric acid, and up to 14,690 cycles of freezing and thawing. PIC shows excellent resistance to sulfate attack, freezing, and thawing, and more than twice the resistance to sulfuric acid as conventional concrete. A study was also conducted to investigate the loss of strength in specimens exposed to sulfuric acid, freezing, and thawing.

- Durability tests on partially impregnated concrete generally show improved resistance to freeze-thaw, acid, and sulfate attack when compared to unimpregnated concrete. Some variations in test results were encountered, which may be due to difficulties in obtaining uniform depths of impregnation within relatively shallow impregnation zones.

- Structural properties on PIC for desalting plant applications included compressive stress-strain relationships and tensile splitting strengths at temperatures ranging from -10°F (-23°C) to 290°F (143°C). The compressive strength of (70-30) MMA-TMPTMA PIC remained about the same at -10°F (-23°C) and 70°F (21°C), but showed a decrease at the elevated temperatures. Tensile splitting tests showed that the strength of (60-40) styrene-TMPTMA PIC remained about the same at temperatures from -10°F (-23°C) to 250°F (121°C) but showed some decrease at 290°F (143°C).

- Specimens impregnated with (60-40) styrene-TMPTMA and (70-30) MMA-TMPTMA were exposed up to 2 years in brine and vapor at temperatures of 250°F (121°C) and 290°F (143°C). The (70-30) MMA-TMPTMA specimens disintegrated after 1 years' exposure to brine and vapor at 290°F (143°C) and could not be tested. The (60-40) styrene-TMPTMA appeared to be in good physical condition after 2 years' exposure to brine and vapor at 250°F (121°C) and 290°F (143°C), although loss in strength and expansion of the specimens were measured and recorded. An examination did not reveal any indications of polymer deterioration, and it is believed that the lower strengths and expansion may be the result of a gradual absorption of small amount of moisture.

Experiences with a variety of nondestructive tests were briefly summarized. These tests included ultrasonic pulse velocity, ultrasonic resonant frequency, acoustic impact, neutron radiography, gamma ray and neutron transmission, infrared radiography, microwave transmission, dielectric and electrical resistivity, and the impact hammer. Further work would be required to develop a suitable method or combination of methods for use with PIC. The more practical approach for quality control would include good process control to insure uniformity of treatment, and destructive type tests of selected specimens to verify product quality.

Final reports were published on PIC applications development for concrete pipe and precast tunnel supports and linings [7 and 8]. Field and laboratory testing is continuing on resistance of PIC draintile to sulfate attack.

A study of FA PCC was completed at Washington State University. The tests showed that compared with conventional concrete, the PCC had similar tensile and compressive strengths, somewhat better resistance to acid, and less resistance to freezing and thawing. Further work would be required to improve the system.

Some of the important general conclusions from the total program are:

- PIC has greatly improved structural properties compared to unimpregnated concrete.

- The durability of PIC is greatly superior to that of unimpregnated concrete. PIC shows excellent freeze-thaw resistance, potentially excellent sulfate attack resistance, and substantial improvement in acid resistance. It appears that PIC could be made to be virtually immune to acid attack by coating the surface with multiple layers of polymer.

- A feasible thermal-catalytic process has been developed for large-scale production of PIC. The process involves drying the concrete, vacuum/pressure impregnation, and polymerization under water.

- Concrete quality and curing conditions are of relatively minor importance in producing good quality PIC. However, it is likely that the best quality and most economical PIC would be produced from good quality, dense concrete.

- MMA, MMA-TMPTMA, and styrene-polyester monomer systems appear promising for PIC applications at normal temperatures. A styrene-TMPTMA monomer system appears promising for PIC in applications under an exposure to brine and vapor at temperatures up to 290°C (143°C), as may be encountered in saline water distillation plants.

- For applications which require good durability rather than high strength, partially impregnated PIC appears to be a less costly alternative to fully impregnated PIC. Further development is required to refine the process for field applications and to determine properties of the material.

- Very promising results have been obtained in the developmental studies on PC (polymer concrete). PC made with a MMA monomer system has structural properties generally comparable to that of PIC and should have much better durability. PC should be substantially less costly to prepare than PIC.

- The limited studies with PCC have not given the desired results. Further work would be required to develop a satisfactory PCC.

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Table 1.—Furfuryl alcohol polymer-cement concrete, compressive and tensile strength

	Conventional concrete		PCC	
	Specimen	lb/in ²	Specimen	lb/in ²
Tensile splitting strength	04	470 [†]	4	380 [†]
	05	500	5	410
	06	440	6	500
	Average	470	Average	430
Compressive strength	01	6,200	*1	6,100
	02	5,900	2	6,000
	03	6,100	**3	6,000
	Average	6,100	Average	6,000
Compressive strength (after vacuum water saturation and ovoidrying at 250°F)	07	7,400	7	9,300
	08	6,800	8	7,500
	09	7,600	9	9,600
	Average	7,200	Average	8,800

3- by 6-inch cylinders.

* Modulus of elasticity = 3.63×10^6 lb/in², Poisson's ratio = 0.17.

** Modulus of elasticity = 3.67×10^6 lb/in², Poisson's ratio = 0.17.

[†] See table 63 to convert to SI metric units.

Table 2.—Furfuryl alcohol polymer-cement concrete, physical properties

	Conventional concrete		PCC	
	Specimen	value	Specimen	value
Water absorption (vacuum saturation), percent by dry weight	07	5.99	7	4.95
	08	5.89	8	4.99
	09	6.47	9	5.06
	Average	6.12	Average	5.00
Specific gravity	07	2.415	7	2.430
	08	2.423	8	2.424
	09	2.414	9	2.430
	Average	2.417	Average	2.430

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Table 3.—Furfuryl alcohol polymer-cement concrete, exposure to 5 percent sulfuric acid

Days exposure	Conventional concrete percent weight loss				PCC percent weight loss			
	Cylinder No.			Average	Cylinder No.			Average
	010	011	012		10	11	12	
16	(2.96)*	(3.14)	(3.57)	(3.22)	(3.53)	(3.69)	(3.70)	(3.64)
34	(3.29)	(3.35)	(3.49)	(3.38)	(3.38)	(3.96)	(3.90)	(3.82)
49	7.43	7.09	6.88	7.13	2.09	0.40	1.74	1.41
79	15.97	17.27	15.58	16.27	7.24	3.87	5.70	5.60
126	28.96	31.44	30.80	30.40	13.82	8.35	11.22	11.13
148	32.56	36.73	35.39	34.89	17.21	9.90	13.95	13.69

* Values in parentheses are a gain in weight.

Table 4.—Furfuryl alcohol polymer-cement concrete, freeze and thaw durability

Freeze-thaw cycles	Conventional concrete percent weight loss				PCC percent weight loss			
	Cylinder No.			Average	Cylinder No.			Average
	013	014	015		13	14	15	
80	1	1	0.5	1	21 Cylinder split	13	7.5	14
180	1.5	4	3.5	3		31	34	33
280	4	5	3.5	4				
380	6	8	10	8				
480	7	8.5	15	10				
580	7	11	31	20				
680	19	18	—	19				
780	23	21	—	22				
880	80	60	—	70				

Weight loss of 25 percent is considered failure.

Table 5.—Strength and physical properties, low-strength concrete impregnated with MMA

Specimen No. 310—	Polymer loading, wt %	Absorption, %	Specific gravity	Compressive strength, lb/in ²	*Tensile strength, lb/in ²
1	10.2	—	—	16,900 [†]	—
2	9.8	—	—	15,400	—
3	10.1	—	—	16,800	—
4	9.3	—	—	16,000	—
5	9.7	—	—	16,500	—
6	9.6	—	—	17,300	—
7	10.1	—	—	—	1,730 [†]
8	9.9	—	—	—	1,950
9	10.1	—	—	—	1,630
10	10.0	1.30	2.28	—	—
11	9.9	1.43	2.27	—	—
12	10.3	1.31	2.27	—	—
Mean	9.9	1.35	2.27	16,500	1,770

3- by 6-inch cylinders.

MMA = methyl methacrylate, thermal-catalytic polymerization.

* Tensile splitting strength.

Concrete mix data:

290 lbs cement/yd³

Water/cement ratio = 0.90

Slump = 2.7 inches

Entrained air = 5.5% gravity, 4.6% pressure

Unit weight = 141.8 lbs/ft³

[†] See table 63 to convert to SI metric units.

Table 6.—*Strength and physical properties, no fines concrete impregnated with MMA*

Specimen No. 311—	Polymer loading, wt %	Absorption, %	Specific gravity	Compressive strength, lb/in ²	*Tensile strength, lb/in ²
1	6.88	—	—	18,400 [†]	—
2	7.05	—	—	22,600	—
3	7.03	—	—	21,400	—
4	7.20	—	—	20,160	—
5	6.63	—	—	22,100	—
6	6.93	—	—	14,360	—
7	6.76	—	—	—	1,670 [†]
8	6.79	—	—	—	1,120
9	7.11	—	—	—	1,780
10	6.67	0.77	2.31	—	—
11	7.22	0.89	2.31	—	—
12	6.87	0.76	2.32	—	—
Mean	6.93	0.81	2.31	20,900	1,520
13	0	—	—	4,700	—
14	0	—	—	4,600	—
15	0	—	—	4,600	—
16	0	—	—	4,800	—
17	0	—	—	4,500	—
18	0	—	—	4,700	—
19	0	—	—	—	390
20	0	—	—	—	360
21	0	—	—	—	350
22	0	6.08	2.28	—	—
23	0	6.28	2.26	—	—
24	0	5.99	2.28	—	—
Mean	0	6.05	2.27	4,700	370

3- by 6-inch cylinders.

MMA = methyl methacrylate, thermal-catalytic polymerization.

* Tensile splitting strength.

Concrete mix data:

Sand grading: 30% No. 50, 30% No. 30, 20% No. 16, 20% No. 8
(contains no sand finer than No. 50 sieve size)

Sand 1,337 lbs/yd³

Gravel 1,610 lbs/yd³

Cement 527 lbs/yd³

Water/cement ratio = 0.47

Slump = 2.5 inches

Entrained air = 9.2% gravity, 7.1% pressure

Unit weight = 137.9 lbs/ft³

[†] See table 63 to convert to SI metric units.

Table 7.—Strength and physical properties, gap-graded concrete impregnated with MMA

Specimen No. 312—	Polymer loading, wt %	Absorption, %	Specific gravity	Compressive strength, lb/in ²	*Tensile strength, lb/in ²
1	6.89	—	—	20,800 [†]	—
2	6.66	—	—	19,500	—
3	6.57	—	—	18,700	—
4	6.82	—	—	21,800	—
5	6.89	—	—	21,400	—
6	6.27	—	—	20,800	—
7	6.47	—	—	—	1,230 [†]
8	6.34	—	—	—	1,240
9	7.02	—	—	—	1,750
10	7.04	0.69	2.33	—	—
11	7.00	0.76	2.33	—	—
12	6.71	1.14	2.33	—	—
Mean	6.72	0.86	2.33	20,500	1,410
13	0	—	—	5,100	—
14	0	—	—	4,900	—
15	0	—	—	4,900	—
16	0	—	—	5,100	—
17	0	—	—	4,900	—
18	0	—	—	4,800	—
19	0	—	—	—	330
20	0	—	—	—	330
21	0	—	—	—	310
22	0	5.89	2.31	—	—
23	0	6.43	2.29	—	—
24	0	5.98	2.31	—	—
Mean	0	6.10	2.30	5,000	320

3- by 6-inch cylinders.

MMA = methyl methacrylate, thermal-catalytic polymerization.

* Tensile splitting strength.

Concrete mix data:

Aggregate contains no No. 4 to 3/8-inch-size gravel

529 lbs cement/yd³

Water/cement ratio = 0.50

Slump = 2.2 inches

Entrained air = 5.9% gravity

Unit weight = 142.4 lbs/ft³

[†] See table 63 to convert to SI metric units.

Table 8.—*Strength and physical properties, CP-type concrete impregnated with MMA*

Specimen No. 313A—	Polymer loading, wt %	Absorption, %	Specific gravity	Compressive strength, lb/in ²	*Tensile strength, lb/in ²
1	5.83	—	—	23,300 [†]	—
2	5.42	—	—	20,100	—
3	5.88	—	—	18,300	—
4	6.03	—	—	18,400	—
5	6.05	—	—	20,400	—
6	5.63	—	—	22,100	—
7	5.48	—	—	—	1,690 [†]
8	5.93	—	—	—	1,660
9	5.76	—	—	—	1,660
10	5.84	0.86	2.37	—	—
11	5.90	0.81	2.36	—	—
12	6.07	0.87	2.34	—	—
Mean	5.82	0.85	2.36	20,400	1,670
13	0	—	—	5,700 [†]	—
14	0	—	—	6,000	—
15	0	—	—	6,000	—
16	0	—	—	6,200	—
17	0	—	—	6,200	—
18	0	—	—	5,900	—
19	0	—	—	—	420 [†]
20	0	—	—	—	370
21	0	—	—	—	390
22	0	6.31	2.35	—	—
23	0	5.98	2.36	—	—
24	0	6.08	2.36	—	—
Mean	0	6.12	2.36	6,000	390

3- by 6-inch cylinders.

MMA = methyl methacrylate, thermal-catalytic polymerization.

* Tensile splitting strength.

CP-type concrete.

[†] See table 63 to convert to SI metric units.

Table 9.—*Sealed moist-storage mortar bar expansion, MMA-impregnated and unimpregnated alkali-reactive 1- by 1- by 10-inch bars*

Age after casting, days	Unimpregnated % expansion*	MMA-impregnated					
		5 days after casting, % expansion*		12 days after casting, % expansion*		33 days after casting, % expansion*	
		Net	After impreg- nation	Net	After impreg- nation	Net	After impreg- nation
1	0	0	—	0	—	0	—
5	—	-0.140	0	—	—	—	—
7	0.052	-0.135	0.005	0.062	—	—	—
12	—	—	—	-0.065	0	—	—
14	0.160	-0.134	0.006	-0.067	-0.002	—	—
21	0.267	-0.128	0.012	-0.061	0.004	—	—
28	0.363	-0.116	0.024	-0.051	0.014	0.378	—
33	—	—	—	—	—	0.213	0
35	0.425	-0.117	0.023	-0.051	0.014	0.209	0.004
42	0.480	-0.113	0.027	-0.049	0.016	0.225	0.012
49	0.580	-0.105	0.035	-0.043	0.022	0.237	0.024
56	0.622	-0.101	0.039	-0.041	0.024	0.240	0.027

* Net expansion is based on measurements at 1 day's age after casting. Expansion after impregnation is based on measurement at time of impregnation. Minus sign indicates a contraction.

Table 10.—Flexure tests of (10-90) polyester-styrene impregnated concrete,
3- by 5- by 54-inch beams tested at room temperature

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE LOAD (LBS.)	MODULUS OF RUPTURE (PSI)	FLEXURAL MODULUS (MILLION PSI)	SHEAR AT ULTIMATE (LBS.)	NOMINAL SHEAR STRESS (PSI)
72.142.6	5.80	6340†	4058†	6.27†	3170†	211†
72.142.7	5.20	6140	3930	6.39	3070	205
72.142.9	5.40	6340	4058	4.27	3170	211
72.142.11	5.80	7180	4595	3.39	3590	239
72.142.12	5.80	6440	4122	4.37	3220	215
MEAN	5.60	6488	4152	4.94	3244	216
STD. DEV.	.28	402	257	1.33	201	13
C OF VAR. (%)	5.05	6.19	6.19	26.89	6.19	6.19

† See table 63 to convert to SI metric units.

Table 11.—Flexure tests of unimpregnated 3- by 5- by 54-inch beams,
controls for (10-90) polyester-styrene impregnated beams
tested at room temperature

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE LOAD (LBS.)	MODULUS OF RUPTURE (PSI)	FLEXURAL MODULUS (MILLION PSI)	SHEAR AT ULTIMATE (LBS.)	NOMINAL SHEAR STRESS (PSI)
71.143.6	.00	6300†	4032†	4.11†	3150†	210†
72.143.7	.00	6240	3994	3.96	3120	208
72.143.8	.00	5660	3622	4.82	2830	189
72.143.9	.00	6100	3904	4.71	3050	203
72.143.10	.00	6160	3942	4.61	3080	205
MEAN	.00	6092	3899	4.44	3046	203
STD. DEV.	.00	253	162	.38	127	8
C OF VAR. (%)	.00	4.16	4.16	8.59	4.16	4.16

† See table 63 to convert to SI metric units.

Table 12.—Flexure tests of polyester-styrene impregnated concrete,
3- by 3- by 16-inch unreinforced bars
tested at room temperature

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE LOAD (LBS.)	MODULUS OF RUPTURE (PSI)	FLEXURAL MODULUS (MILLION PSI)	SHEAR AT ULTIMATE (LBS.)	NOMINAL SHEAR STRESS (PSI)
72.144.1	5.70	7400†	2878†	5.34†	3700†	411†
72.144.2	5.50	6700	2606	6.46	3350	372
72.144.3	6.00	6480	2520	5.15	3240	360
72.144.4	5.80	7000	2722	5.98	3500	389
72.144.5	4.70	4180	1626	4.88	2090	232
MEAN	5.54	6352	2470	5.56	3176	353
STD. DEV.	.50	1262	491	.65	631	70
C OF VAR. (%)	9.08	19.87	19.87	11.61	19.87	19.87

† See table 63 to convert to SI metric units.

Table 13.—Flexure tests of unimpregnated concrete 3- by 3- by 16-inch bars,
controls for (10-90) polyester-styrene impregnated bars
tested at room temperature

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE LOAD (LBS.)	MODULUS OF RUPTURE (PSI)	FLEXURAL MODULUS (MILLION PSI)	SHEAR AT ULTIMATE (LBS.)	NOMINAL SHEAR STRESS (PSI)
72.145.1	.00	2460†	957†	4.76†	1230†	137†
72.145.2	.00	2460	957	4.56	1230	137
72.145.3	.00	2300	894	5.00	1150	128
72.145.4	.00	2480	964	4.96	1240	138
72.145.5	.00	2420	941	5.13	1210	134
MEAN	.00	2424	943	4.88	1212	135
STD. DEV.	.00	73	28	.22	36	4
C OF VAR. (%)	.00	3.00	3.00	4.57	3.00	3.00

† See table 63 to convert to SI metric units.

Table 14.—*Shear tests, control and (10-90) polyester-styrene impregnated concrete
3- by 5- by 54-inch beams at room temperature*

Specimen No.	Polymer loading, wt %	Ultimate load, lbs	Ultimate shear, lbs	Nominal shear stress, lb/in ²	Ultimate moment, in-lb
72.142.1	5.2	23,100 [†]	18,900 [†]	1,480 [†]	47,250 [†]
72.142.2	5.6	19,800	16,200	1,270	40,500
72.142.3	5.6	20,660	16,900	1,325	42,260
72.142.4	5.5	25,600	20,950	1,645	52,360
72.142.5	4.4	24,700	20,210	1,585	50,520
Mean	5.26	22,772	18,632	1,461	46,578
Std Dev	0.508	2,506	2,052	162	5,124
C of Var. (%)	9.66	11.01	11.01	11.07	11.00
72.143.1	0	12,200	9,980	785	24,950
72.143.2	0	11,560	9,460	740	23,650
72.143.3	0	13,300	10,880	885	27,200
72.143.4	0	14,100	11,540	905	28,840
72.143.5	0	12,500	10,230	800	25,570
Mean	0	12,732	10,418	817	26,042
Std Dev	0	988	809	64.1	2,019
C of Var. (%)	0	7.76	7.76	7.84	7.75

[†] See table 63 to convert to SI metric units.

Table 15.—Compressive strength of creep test specimens,
3 to 4-1/2 years under 800-lb/in² sustained load —
CP test series

Specimen No.	Monomer	Polymer loading, percent by wt	Method of polymerization initiation	Time under 800 lb/in ² load, yrs	After creep test compressive, strength, lb/in ²	Compressive str. of companion control cyls never loaded
CP-1A-7A	MMA	5.7	R	4-1/2	21,750 [†]	
CP-1A-7C	MMA	5.9	R	4-1/2	22,820	23,350 [†]
CP-1B-7A	MMA	6.2	T	4-1/2	19,560	
CP-1B-7B	MMA	6.2	T	4-1/2	19,670	20,200
CP-2A-7A	S	5.6	R	4-1/2	17,400	
CP-2A-7B	S	6.0	R	4-1/2	16,310	16,550
CP-2B-7B	S	5.1	T	4-1/2	13,480	
CP-2B-7X	S	3.5	T	4-1/2	10,750	—
CP-5A-7A	AN	5.7	R	3	16,910	
CP-5A-7B	AN	5.7	R	3	18,110	16,340
CP-5B-7A	AN	4.4	T	3	7,110	
CP-5B-7B	AN	5.4	T	3	7,320	7,780
CP-6A-7A	CS	6.7	R	3	19,740	
CP-6A-7B	CS	6.9	R	3	19,420	19,100
CP-6B-7A	CS	6.2	T	3	15,350	
CP-6B-7B	CS	6.5	T	3	15,630	14,930
CP-0 -7B	None	—	—	4-1/3	6,610	
CP-0 -7C	None	—	—	4-1/3	6,460	6,440
CP-3A-7A	None	—	—	4-1/3	6,370	
CP-3A-7B	None	—	—	4-1/3	6,140	5,960
CP-3B-7A	None	—	—	4-1/3	6,310	
CP-3B-7B	None	—	—	4-1/3	5,940	5,980

6- by 12-inch cylinders.

Specimens oven-dried at 105°C (221°F) prior to impregnation.

R = radiation.

T = thermal-catalytic.

MMA = methyl methacrylate.

S = styrene.

AN = acrylonitrile.

CS = monochlorostyrene.

[†] See table 63 to convert to SI metric units.

Table 16.—Resistance to sulfate attack —
CP test series

Specimen No.	Monomer	Polymer loading, wt %	Method of polymerization	Test cycles, days	Net expansion, %
Control	None	-	None	1,486	<u>3/</u> 0.550
MMA-10	*MMA	6.3	R	2,044	- .030
S-14	*S	6.2	R	2,109	.016
CP-0-4A	None	-	None	480	<u>3/</u> .502
CP-0-4B	None	-	None	480	<u>3/</u> .432
CP-1A-4A	MMA	6.1	R	540	<u>2/</u> .016
CP-1A-4B	MMA	6.6	R	1,853	.024
CP-1B-4A	MMA	6.3	T	1,853	.028
CP-1B-4B	MMA	6.6	T	1,853	.016
CP-2A-4A	S	5.1	R	1,814	.036
CP-2A-4B	S	5.7	R	1,814	.042
CP-2B-4B	S	4.5	T	1,814	.042
CP-3A-4A	None	-	R	750	<u>3/</u> .580
CP-3A-4B	None	-	R	750	<u>3/</u> .536
CP-3B-4A	None	-	T	605	<u>3/</u> .496
CP-3B-4B	None	-	T	605	<u>3/</u> .548
CP-4A-4A	MMA+TMPTMA	6.1	R	360	<u>2/</u> .004
CP-4A-4B	MMA+TMPTMA	6.5	R	1,679	.020
CP-4B-4A	MMA+TMPTMA	7.4	T	1,679	.016
CP-4B-4B	MMA+TMPTMA	7.2	T	1,679	.002
CP-5A-4A	AN	5.1	R	540	<u>3/</u> .462
CP-5A-4B	AN	5.3	R	180	<u>1/</u> .096
CP-5B-4A	AN	5.0	T	390	<u>1/</u> .150
CP-5B-4B	AN	6.0	T	1,651	.016
CP-6A-4A	CS	5.1	R	732	<u>3/</u> .466
CP-6A-4B	CS	5.8	R	732	<u>3/</u> .798
CP-6B-4A	CS	6.3	T	1,296	.028
CP-6B-4B	CS	6.6	T	1,296	.024
CP-7-4A	PE-S	6.6	R	595	.010
CP-7-4B	PE-S	6.8	R	595	.000
CP-UA-4A	MMA	7.1	R	752	.024
CP-UA-4B	MMA	6.7	R	752	.020

3- by 6-inch specimens, oven-dried at 105°C (221°F) prior to impregnation.

*Specimens not oven-dried.

R = Radiation.

T = Thermal-catalytic.

MMA = Methyl methacrylate.

S = Styrene.

TMPTMA = Trimethylolpropane trimethacrylate.

MMA+TMPTMA = MMA + 10 wt % TMPTMA.

AN = Acrylonitrile.

CS = Chlorostyrene.

PE-S = (10-90) Polyester-styrene.

1/ Loose insert from specimen deterioration, removed from test.

2/ Removed from test for display.

3/ Specimen failed, removed from test.

Table 17.—Resistance to freezing and thawing —
CP test series

Specimen No.	Monomer	Polymer loading, wt %	Method of polymerization	Number of test cycles	Weight loss, %
Control	None	-	None	2/ 590	26.5
BNL-1-3	*MMA	6.7	R	14,690	2.0
CP-0-3A	None	-	None	2/ 490	25.0
CP-0-3B	None	-	None	2/ 990	26.0
CP-1A-3A	MMA	5.9	R	1/ 8,310	9.0
CP-1A-3B	MMA	5.9	R	3/ 10,340	12.5
CP-1B-3A	MMA	6.9	T	1/ 3,650	1.5
CP-1B-3B	MMA	6.9	T	1/ 3,650	2.0
CP-2A-3A	S	4.8	R	2/ 2,010	25.0
CP-2A-3B	S	4.9	R	2/ 3,260	26.0
CP-2B-3A	S	4.5	T	2/ 6,290	25.0
CP-2B-3B	S	4.3	T	2/ 5,740	26.0
CP-3A-3A	None	-	R	2/ 390	30.0
CP-3A-3B	None	-	R	2/ 490	26.0
CP-3B-3A	None	-	T	2/ 440	40.0
CP-3B-3B	None	-	T	2/ 440	30.0
CP-4A-3A	MMA+TMPTMA	6.2	R	2/ 3,350	33.0
CP-4A-3B	MMA+TMPTMA	6.2	R	2/ 7,870	24.5
CP-4B-3A	MMA+TMPTMA	7.2	T	1/ 1,230	0.5
CP-4B-3B	MMA+TMPTMA	7.1	T	11,130	8.0
CP-5A-3A	AN	5.1	R	2/ 1,840	25.0
CP-5A-3B	AN	5.0	R	2/ 1,540	25.0
CP-5B-3A	AN	5.6	T	1/ 2/ 9,420	23.0
CP-5B-3A	AN	5.3	T	2/ 8,710	25.0
CP-6A-3A	CS	6.3	R	2/ 2,000	25.0
CP-6A-3B	CS	6.3	R	2/ 1,800	25.0
CP-6B-3A	CS	6.3	T	2/ 4,710	25.0
CP-6B-3B	CS	6.5	T	2/ 4,610	25.0
CP-UA-3A	MMA	7.1	R	2/ 3/ 4,560	>25.0
CP-UA-3B	MMA	6.9	R	2/ 3/ 4,560	>25.0
CP-7-3A	PE-S	7.0	R	2/ 3/ 3,310	>25.0
CP-7-3B	PE-S	6.9	R	4,210	3.5

3- by 6-inch cylinders, oven-dried at 105°C (221°F) prior to impregnation.

* Specimen not oven-dried prior to impregnation.

R = Radiation.

T = Thermal-catalytic.

MMA = Methyl methacrylate.

S = Styrene.

TMPTMA = Trimethylolpropane trimethacrylate.

MMA+TMPTMA = MMA + 10 wt % TMPTMA.

AN = Acrylonitrile.

CS = Chlorostyrene.

PE-S = (10-90) polyester-styrene.

1/ Removed from test.

2/ Failed and removed from tests, weight loss over 25 percent.

3/ Specimen split into two pieces.

Table 18.—Resistance to 5 percent sulfuric acid, polymer-impregnated concrete

Monomer	Specimen No.	Polymer loading, wt %	Percent weight loss							Compressive strength, lb/in ² (after sulfate test failure)
			174 days	210 days	252 days	290 days	326 days	423 days	459 days	
PE-S	CP-7									
	17A	6.6	—	18.5	17.5	—	21.2	—	¹ 31.9	6,210 [†]
	19B	6.9	—	13.0	16.3	—	18.0	—	¹ 35.0	4,840
MMA*	CP-UA									
	19A	7.3	—	15.4	13.2	—	15.4	—	¹ 26.9	4,360
	19B	7.1	—	17.0	21.3	—	25.4	—	30.4	4,790
PE-S	CP-R									
	2	6.5	13.4	14.5	—	18.7	—	¹ 27.9	—	8,700
	22	6.6	12.7	14.2	—	18.3	—	¹ 26.8	—	6,240
	23	6.4	12.8	14.6	—	18.3	—	¹ 26.2	—	5,910
	51	6.5	12.0	13.4	—	17.3	—	¹ 25.2	—	5,280
	64	6.3	13.4	15.0	—	19.3	—	¹ 28.2	—	6,090
	72	6.4	13.4	16.4	—	20.9	—	¹ 28.9	—	4,190
MMA	CP.									
	4B-15A	6.5	8.8	10.2	—	13.3	—	20.1	—	—
	4B-15D	5.6	14.6	18.5	—	23.5	—	¹ 31.8	—	7,470
	5B-11A	6.3	13.1	15.9	—	20.3	—	¹ 27.8	—	8,630
	5B-12D	5.6	11.0	13.0	—	16.7	—	23.2	—	—
	5B-14A	5.4	11.6	14.7	—	19.3	—	¹ 27.3	—	7,690
	5B-15B	6.0	11.1	13.3	—	16.2	—	¹ 25.0	—	7,160
Unimpregnated	CP-DP									
	76	0	—	¹ 33.8	—	—	—	—	—	—
	82	0	—	¹ 32.4	—	—	—	—	—	—

3- by 6-inch specimens, oven-dried at 110°C (230°F) prior to impregnation.

PE-S = (10-90) polyester-styrene.

MMA = methyl methacrylate, radiation polymerization.

* Radiation polymerization under water.

¹ Failed, weight loss greater than 25%.

[†] See table 63 to convert to SI metric units.

Table 19.—Weight loss after exposure to freezing and thawing

Exposure time, cycles	MMA-impregnated concrete				Unimpregnated concrete			
	Cylinders		Prisms		Cylinders		Prisms	
	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %
100	37	(0.1)*	2	0	50	0.3	3	0.7
200	37	(0.1)	2	0	49	0.8	3	0.9
300	27	0.3	—	—	40	1.4	—	—
350	8	0.2	2	(0.1)*	4	1.3	3	1.1
400	27	0.5	—	—	40	2.1	—	—
500	32	0.4	2	0	44	2.6	3	1.2
600	24	0.7	—	—	37	4.8	—	—
700	29	0.7	2	(0.1)	41	6.1	3	1.7
800	24	0.8	2	0	29	8.7	3	2.0
850	5	0.3	2	0	4	5.2	3	1.9
900	18	0.8	—	—	19	10.1	—	—
1000	18	0.7	2	0.1	18	12.5	3	2.7
1300	15	0.8	2	0.2	8	12.9	3	3.5

*Percentages in parentheses are a gain in weight.

Specimens: cylinders, 3- by 6-inches.

prisms, 3- by 3- by 16-inches.

MMA = methyl methacrylate.

Table 20.—Compressive strength after exposure to freezing and thawing

Exposure time, cycles	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Compressive strength,		Loss in strength, %	No. of specimens	Compressive strength,		Loss in strength, %
		lb/in ²	MPa			lb/in ²	MPa	
0	8	21,100	146	—	12	4300	30	—
200	3	21,600	149	0	3	4700	32	0
500	3	20,300	140	3.8	3	4200	29	2.3
700	—	—	—	—	3	4200	29	2.3
800	3	15,300	105	27.5	3	3500	24	18.6
900	3	19,300	133	8.5	3	2900	20	32.6
1000	3	18,000	124	14.7	3	3000	21	30.2
1300	3	19,300	133	8.5	2	3200	22	25.6

3- by 6-inch cylindrical specimens.

MMA = methyl methacrylate.

Table 21.—Tensile splitting strength after exposure to freezing and thawing

Exposure time, cycles	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Tensile splitting strength,		Loss in strength, %	No. of specimens	Tensile splitting strength,		Loss in strength, %
		lb/in ²	MPa			lb/in ²	MPa	
0	3	1430	9.9	—	3	430	3.0	—
200	3	1250	8.6	12.6	—	—	—	—
700	—	—	—	—	3	570	3.9	0
800	—	—	—	—	3	450	3.1	0
1000	3	1300	9.0	9.1	3	440	3.0	0
1300	3	1690	11.6	0	1	710	5.3	0

3- by 6-inch cylindrical specimens.
MMA = methyl methacrylate.

Table 22.—Pulse velocity after exposure to freezing and thawing

Exposure time, cycles	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Pulse velocity,		Loss in pulse velocity, %	No. of specimens	Pulse velocity,		Loss in pulse velocity, %
		ft/s	m/s			ft/s	m/s	
0	5	18,300	5580	—	4	15,700	4790	—
100	5	16,600	5060	9.3	4	14,000	4270	10.8
200	5	16,600	5060	9.3	4	14,200	4330	9.6
350	5	16,600	5060	9.3	4	14,400	4390	8.3
500	5	15,800	4820	13.7	4	13,900	4240	11.5
700	5	16,200	4940	11.5	4	13,500	4110	14.0
850	5	15,900	4850	13.1	4	13,200	4020	15.9
1000	4	15,600	4750	14.8	4	12,200	3720	22.3
1300	5	15,600	4750	14.8	4	12,000	3660	23.6

3- by 6-inch cylindrical specimens.
MMA = methyl methacrylate.

Table 23.—*Dynamic modulus of elasticity after exposure to freezing and thawing*

Exposure time, cycles	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Modulus of elasticity,		% change	No. of specimens	Modulus of elasticity,		% change
		10 ⁶ lb/in ²	GPa			10 ⁶ lb/in ²	GPa	
0	2	5.50	3.79	—	3	5.12	3.53	—
200	2	5.41	3.73	-1.6	2	5.20	3.59	+1.6
350	2	5.28	3.64	-4.0	3	4.98	3.43	-2.7
500	1	5.24	3.61	-4.7	3	4.89	3.37	-4.5
700	2	5.39	3.72	-2.0	3	4.68	3.23	-8.6
800	2	5.39	3.72	-2.0	3	4.61	3.18	-10.0
850	2	5.24	3.61	-4.7	3	4.62	3.19	-9.8
1000	2	5.12	3.53	-6.9	3	4.65	3.21	-9.2
1300	2	5.13	3.54	-6.7	3	4.64	3.20	-9.5

3- by 3- by 16-inch prisms.
MMA = methyl methacrylate.

Table 24.—*Length change after exposure to freezing and thawing*

Exposure time, cycles	MMA-impregnated concrete		Unimpregnated concrete	
	No. of specimens	Length change, %	No. of specimens	Length change, %
100	2	-0.020	3	+0.002
200	2	-0.007	3	+0.005
350	2	-0.018	3	+0.006
500	2	-0.012	3	+0.014
700	2	-0.013	3	+0.017
800	2	-0.004	3	+0.023
850	2	-0.007	3	+0.024
1000	2	-0.004	3	+0.032
1300	2	0.000	3	+0.034

3- by 3- by 16-inch prisms.
MMA = methyl methacrylate.

Table 25.—*Weight loss after exposure to 5 percent sulfuric acid*

Exposure time, days	MMA-impregnated concrete				Unimpregnated concrete			
	Cylinders		Prisms		Cylinders		Prisms	
	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %	No. of specimens	Weight loss, %
7	37	(0.1)*	2	0	44	1.2	3	3.2
14	34	(0.1)	—	—	41	4.0	—	—
28	10	(0.3)	2	(0.2)*	9	6.4	3	7.2
49	29	(0.8)	2	0	36	6.4	3	11.5
70	11	(1.1)	2	(0.2)	11	10.2	3	13.6
98	20	(0.6)	2	1.5	26	17.5	3	19.7
105	3	2.5	—	—	3	20.6	—	—
112	5	(0.2)	2	1.8	4	27.2	3	23.5
120	17	0.6	2	1.9	18	24.0	3	24.2
140	14	1.0	2	4.3	12	33.2	3	30.2
170	5	2.9	2	5.5	4	47.0	3	41.3

*Percentages in parentheses are a gain in weight.

Specimens: cylinders, 3- by 6-inches.

prisms, 3- by 3- by 16-inches.

MMA = methyl methacrylate.

Table 26.—*Compressive strength after exposure to 5 percent sulfuric acid*

Exposure time, days	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Compressive strength,		Loss in strength, %	No. of specimens	Compressive strength,		Loss in strength, %
		lb/in ²	MPa			lb/in ²	MPa	
0	8	21,100	146	—	12	4,300	30	—
7	3	21,300	147	0	3	4,200	29	2.4
28	3	21,500	148	0	3	4,800	33	0
49	3	19,300	133	8.5	3	4,600	32	0
70	4	20,100	139	4.7	3	4,000	28	7.0
98	—	—	—	—	3	2,800	19	34.9
105	3	14,700	101	30.3	3	3,900	27	9.3
120	3	15,800	109	25.1	3	2,900	20	32.6
140	3	18,900	130	10.4	3	2,700	19	37.2
170	3	11,800	81	44.1	2	1,500	10	65.1

3- by 6-inch cylindrical specimens.

MMA = methyl methacrylate.

Table 27.—Tensile splitting strength after exposure to 5 percent sulfuric acid

Exposure time, days	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Tensile splitting strength,		Loss in strength, %	No. of specimens	Tensile splitting strength,		Loss in strength, %
		lb/in ²	MPa			lb/in ²	MPa	
0	3	1,430	9.9	—	3	430	3.0	—
28	2	1,970	13.6	0	2	750	5.2	0
70	3	1,980	13.7	0	3	680	4.7	0
98	—	—	—	—	3	400	2.8	7.0
120	—	—	—	—	3	350	2.4	18.6
140	—	—	—	—	3	520	3.6	0
170	3	1,630	11.2	0	—	—	—	—

3- by 6-inch cylindrical specimens.
MMA = methyl methacrylate.

Table 28.—Pulse velocity after exposure to 5 percent sulfuric acid

Exposure time, days	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Pulse velocity,		Loss in pulse velocity, %	No. of specimens	Pulse velocity,		Loss in pulse velocity, %
		ft/s	m/s			ft/s	m/s	
0	5	18,100	5520	—	4	15,000	4570	—
14	5	17,000	5180	6.1	4	13,300	4050	11.3
28	5	15,600	4750	13.8	4	12,000	3660	20.0
49	5	14,100	4300	22.1	4	11,600	3540	22.7
70	5	10,900	3320	39.8	4	13,000	3960	13.3
98	5	9,900	3020	45.3	3	12,200	3720	18.6
120	5	11,400	3470	37.0	4	13,300	4050	11.3
140	5	11,300	3440	37.6	4	13,600	4150	9.3
170	5	9,600	2930	47.0	4	12,700	3870	15.3

3- by 6-inch cylindrical specimens.
MMA = methyl methacrylate.

Table 29.—*Dynamic modulus of elasticity after exposure to 5 percent sulfuric acid*

Exposure time, days	MMA-impregnated concrete				Unimpregnated concrete			
	No. of specimens	Modulus of elasticity,		% change	No. of specimens	Modulus of elasticity,		% change
		10 ⁶ lb/in ²	GPa			10 ⁶ lb/in ²	GPa	
0	2	5.39	3.72	—	3	4.77	3.29	—
28	2	5.19	3.58	-3.7	3	4.51	3.10	-5.5
49	2	5.29	3.65	-1.9	3	4.57	3.15	-4.2
70	1	5.40	3.72	+0.1	—	—	—	—
98	1	5.50	3.79	+2.0	3	3.58	2.47	-24.9
112	1	5.30	3.65	-1.7	3	3.58	2.47	-24.9
120	2	5.35	3.69	-0.7	3	3.35	2.31	-29.8
140	2	5.35	3.69	-0.7	1	3.00	2.07	-37.1
170	2	5.17	3.56	-4.1	3	2.47	1.70	-48.2

3- by 3- by 16-inch prisms.

MMA = methyl methacrylate.

Table 30.—*Length change after exposure to 5 percent sulfuric acid*

Exposure time, days	MMA-impregnated concrete		Unimpregnated concrete	
	No. of specimens	Length change, %	No. of specimens	Length change, %
14	2	+0.012	3	+0.004
28	2	+0.011	3	+0.015
49	2	+0.002	3	+0.012
70	2	+0.012	3	+0.017
98	1	+0.021	3	+0.021
112	1	+0.015	3	+0.029
120	2	+0.015	3	+0.016
140	2	+0.014	3	+0.026
170	2	+0.012	3	+0.034

3- by 3- by 16-inch prisms.

MMA = methyl methacrylate.

Table 31.—Resistance to freezing and thawing, partially impregnated concrete—
second test series

Specimen No.	Polymer	Nominal penetration depth, in.	Polymer loading, wt %	Water absorption, %	Number of cycles	Weight loss, %
CP-DP-83	PE-S	1/2 [†]	5.3	0.2	4,280	¹ (6.0)* Split
CP-DP-95	PE-S	1/2	6.0	0.2	4,480	¹ (0.5) Split
CP-DP-79	PE-S	3/8	4.0	0.3	4,280	¹ (1.0) Split
CP-DP-81	PE-S	3/8	3.5	0.4	4,280	¹ (0.5) Split
CP-DP-80	PE-S	1/4	3.0	0.4	4,080	¹ (2.5) Split
CP-DP-93	PE-S	1/4	3.0	0.3	3,780	¹
CP-DP-91	PMMA	1/2	5.6	0.2	4,580	0
CP-DP-100	PMMA	1/2	4.9	0.3	4,580	6.0
CP-DP-74	PMMA	3/8	5.3	0.2	4,580	9.0
CP-DP-77	PMMA	3/8	4.5	0.5	4,580	21.0
CP-DP-75	PMMA	1/4	4.4	0.1	4,580	(2.5)
CP-DP-88	PMMA	1/4	4.3	0.1	4,580	(3.0)
CP-DP-92	Control	—	—		2,200	¹ 13.0 Split
CP-DP-101	Control	—	—		2,150	¹ 25.0

*Percentages in parentheses indicate a gain in weight.

3- by 6-inch cylinders oven-dried at 104°C (220°F) prior to impregnation.

Radiation-initiated polymerization.

PE-S = 50 percent polyester (Plaskon) plus 50 percent styrene, viscosity 70 cP.

PMMA = PMMA prepolymer, produced by irradiating MMA to a viscosity of 70 cP.

¹ Failed and removed from tests, weight loss over 25 percent. Weight losses reported for specimens failing by splitting include both fragments.

[†] See table 63 to convert to SI metric units.

Table 32.—Resistance to sulfate attack, partially impregnated concrete—
first test series

Specimen No.	Monomer	Nominal penetration depth, in.	Test cycles, days	Net expansion, %
CP-DP-49	—	0	1,167	0.536
CP-DP-50	—	0 failed	1,167	.561
CP-DP-20	E-S	1/16 [†]	1,274	.200
CP-DP-11	E-S	1/16	1,274	.206
CP-DP-39	E-S	1/8	1,274	.138
CP-DP-12	E-S	1/8	1,274	.098
CP-DP-24	E-S	1/4	1,274	.712
CP-DP-43	E-S	1/4	1,274	.234
CP-DP-22	PE-S	1/16	1,167	.708
CP-DP-15	PE-S	1/16 failed	1,167	.484
CP-DP-2	PE-S	1/8	1,274	.276
CP-DP-34	PE-S	1/8	1,274	.084
CP-DP-9	PE-S	1/4	1,274	.080
CP-DP-26	PE-S	1/4	1,274	.074

3- by 6-inch specimens oven-dried at 150°C (302°F) prior to impregnation.

Radiation-initiated polymerization.

EP-S = epoxy-styrene.

PE-S = polyester-styrene.

[†] See table 63 to convert to SI metric units.

Table 33.—Resistance to sulfate attack, partially impregnated concrete—
second test series

Specimen No.	Polymer	Nominal penetration depth, in.	Polymer loading, wt %	Absorption, wt %	Test cycles, days	Net expansion, percent
CP-DP-60	PE-S	1/12 [†]	5.1	0.3	577	0.006
CP-DP-72	PE-S	1/12	5.2	0.2	577	.006
CP-DP-68	PE-S	3/8	3.3	0.3	577	.010
CP-DP-69	PE-S	3/8	3.4	0.6	577	¹ .056
CP-DP-59	PE-S	1/4	3.1	0.6	577	¹ .062
CP-DP-70	PE-S	1/4	2.6	0.8	577	.054
CP-DP-58	PMMA	1/2	5.5	0.3	577	.038
CP-DP-62	PMMA	1/2	6.1	0.2	577	.020
CP-DP-66	PMMA	3/8	4.3	0.4	577	.032
CP-DP-73	PMMA	3/8	4.5	0.4	577	.032
CP-DP-57	PMMA	1/4	4.6	0.2	577	.014
CP-DP-71	PMMA	1/4	4.6	0.1	577	.014
CP-DP-63	None	—	—	—	577	.130
CP-DP-67	None	—	—	—	577	.120

3- by 6-inch specimens oven-dried at 104°C (220°F).

PE-S = 50 percent polyester (Plaskon) plus 50 percent styrene, viscosity to 70 cP.

PMMA = PMMA prepolymer, produced by irradiating MMA to a viscosity of 70 cP.

¹ Fine cracks appeared at 60 days.

[†] See table 63 to convert to SI metric units.

Table 34.—Resistance to 5 percent sulfuric acid, partially impregnated concrete—
second test series

Monomer	Specimen No. CP-DP	Nominal penetration depth, in.	Polymer loading, wt %	Absorption, wt %	Percent weight loss,			
					210 days	252 days	326 days	459 days
PE-S	115	1/2 [†]	5.4	0.1	23.4	¹ 26.8	32.7	41.3
	118	1/2	5.0	0.2	21.7	¹ 24.9	29.1	36.5
	96	3/8	3.8	0.4	22.6	¹ 24.6	29.7	42.9
	110	3/8	3.9	0.4	22.1	¹ 24.6	30.1	42.7
	94	1/4	3.2	0.6	22.6	22.6	¹ 27.2	43.9
	108	1/4	3.0	0.5	20.3	20.4	24.0	¹ 40.0
PMMA	109	1/2	5.0	0.2	20.7	20.0	¹ 25.2	39.7
	113	1/2	5.2	0.2	21.4	22.3	¹ 29.3	44.7
	90	3/8	3.3	0.3	22.9	¹ 27.6	35.0	51.4
	97	3/8	4.5	0.4	24.6	¹ 28.3	38.6	55.1
	89	1/4	4.1	0.1	19.7	¹ 20.9	¹ 27.0	44.9
	98	1/4	4.9	0.1	15.7	16.4	21.0	¹ 33.8
Unimpregnated	76	—	0	—	¹ 33.8	—	—	—
	82	—	0	—	¹ 32.4	—	—	—

3- by 6-inch specimens oven-dried at 104°C (220°F) prior to impregnation.

PE-S = (50-50) polyester (Plaskon) — styrene, viscosity 70 cP.

PMMA = methyl methacrylate prepolymer, produced by irradiating MMA to a viscosity of 70 cP.

Radiation-initiated polymerization.

¹ Failed, weight loss greater than 25%.

[†] See table 63 to convert to SI metric units.

Table 35.—Resistance to 5 percent sulfuric acid, partially impregnated CP-type concrete—
third test series

Monomer	Specimen No. 72—	Nominal penetration depth, in.	Polymer loading, wt %	Water absorption, % dry wt	Percent weight loss,		
					259 days	318 days	434 days
PE-S	16-7	1/4 [†]	2.5	5.2	9.1	21.0	22.9
	8	1/4	2.3	5.5	8.6	21.6	¹ 31.7
	9	1/4	2.2	5.0	8.7	19.7	¹ 41.0
	4	3/8	4.9	2.6	9.7	16.2	24.6
	5	3/8	4.6	1.9	10.9	17.8	¹ 25.8
	6	3/8	4.7	2.5	9.4	16.5	¹ 25.3
	1	1/2	5.7	1.7	12.1	19.3	¹ 28.8
	2	1/2	5.2	2.1	11.2	17.9	¹ 26.8
	3	1/2	5.8	1.3	10.2	16.2	24.3
	16-17	1/4	2.3	5.2	12.6	23.9	¹ 44.5
	19	1/4	3.0	0.8	7.6	13.5	¹ 30.1
	20	1/4	2.6	3.0	10.2	16.7	¹ 32.1
PMMA	11	3/8	3.9	2.3	7.5	9.0	18.1
	13	3/8	3.3	1.7	11.1	17.4	¹ 28.2
	15	3/8	3.7	3.0	11.8	17.9	¹ 46.1
	10	1/2	4.1	1.1	6.8	8.0	14.9
	12	1/2	4.5	1.2	2.5	3.1	13.9
	14	1/2	4.6	2.1	9.9	15.7	¹ 25.6
Unimpregnated	17-1	—	—	6.6	¹ 38.9	—	—
	2	—	—	6.9	15.3	¹ 34.8	—
	3	—	—	6.7	¹ 33.5	—	—
	4	—	—	6.3	21.7	¹ 37.3	—
	5	—	—	6.9	14.3	¹ 31.6	—
	6	—	—	6.3	¹ 42.5	—	—

CP-type concrete, 3- by 6-inch specimens oven-dried at 110°C (230°F).

Radiation-initiated polymerization.

PE-S = (50-50) polyester-styrene, 40 cP viscosity.

PMMA = 20 percent solution of PMMA in methyl methacrylate, 60 cP viscosity.

¹ Failed, weight loss greater than 25%.

[†] See table 63 to convert to SI metric units.

Table 36.—Resistance to 5 percent sulfuric acid, partially impregnated high-entrained air concrete—
third test series

Monomer	Specimen No. 72—	Nominal penetration depth, in.	Polymer loading, wt %	Water absorption, % dry wt	Percent weight loss,		
					259 days	318 days	434 days
PE-S	45-5	1/4 [†]	4.6	6.4	8.7	15.4	23.4
	6	1/4	4.2	6.0	8.5	14.5	20.8
	7	1/4	4.7	5.5	8.7	14.4	¹ 28.0
	1	3/8	5.1	4.4	8.5	14.0	24.0
	2	3/8	4.9	5.3	10.4	18.5	¹ 27.1
	4	3/8	5.1	4.7	9.7	15.4	¹ 23.8
	8	1/2	7.7	0.7	14.5	18.7	¹ 25.8
	9	1/2	7.8	0.6	14.4	21.0	¹ 27.4
	10	1/2	8.0	0.7	16.3	¹ 25.1	—
PMMA	45-20	1/4	3.7	7.5	9.2	14.7	¹ 30.4
	21	1/4	3.7	8.2	8.9	10.3	24.6
	24	1/4	3.9	6.4	9.1	13.7	¹ 41.6
	17	3/8	5.5	1.3	7.5	10.7	16.2
	18	3/8	5.7	2.4	11.3	17.6	19.2
	19	3/8	5.5	2.4	7.5	8.2	15.2
	12	1/2	7.8	1.9	8.3	10.7	20.7
	13	1/2	7.9	1.4	7.8	10.5	16.4
	15	1/2	8.0	1.7	8.5	11.6	18.5
Unimpregnated	46-1	—	—	6.2	¹	—	—
	2	—	—	5.7	¹	—	—
	3	—	—	6.3	¹ 35.7	—	—
	5	—	—	6.4	¹ 55.9	—	—
	6	—	—	6.3	¹ 34.4	—	—

High-entrained air concrete, CP-type concrete mix adjusted to give 11.2 percent entrained air, 3- by 6-inch specimens
ovendried at 110°C (230°F).

Radiation-initiated polymerization.

PE-S = (50-50) polyester-styrene, 40 cP viscosity.

PMMA = 20 percent solution of PMMA in methyl methacrylate, 60 cP viscosity.

¹ Failed, weight loss greater than 25 percent.

[†] See table 63 to convert to SI metric units.

Table 37.—Compressive stress-strain tests of (70-30) MMA-TMPTMA impregnated
6- by 12-inch cylinders after 6 months' exposure at -10°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.191.4	6.90	17860†	.18	5.70†	9000†	3360
72.191.5	6.10	19740	.16	6.02	14000	3420
72.191.12	6.70	18460	.18	6.18	11000	3250
72.191.14	5.90	16840	.20	6.35	11000	3020
72.191.22	7.20	15950	.20	5.85	12000	2900
72.191.23	6.90	16160	.20	5.85	11000	2900
72.191.25	6.70	16690	.19	5.72	12000	3040
72.191.31	6.90	17540	.18	5.76	14000	3300
72.191.38	7.80	17830	.24	5.86	11000	3380
72.191.41	6.70	14750	.21	6.32	8000	3050
MEAN	6.78	17182	.197	5.961	11300	3162
STD. DEV.	.53	1414	.0209	.2111	1889	201
CO OF VA %	7.80	8.23	10.61	3.54	16.71	6.37

† See table 63 to convert to SI metric units.

Table 38.—Compressive stress-strain tests of (70-30) MMA-TMPTMA impregnated
6- by 12-inch cylinders after 6 months' exposure at 70°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.191.1	6.90	17150†	.19	5.78†	10000†	3380
72.191.9	6.10	18040	.21	6.45	10000	3080
72.191.18	6.90	18070	.20	6.18	9000	3260
72.191.26	7.10	16840	.21	5.87	10000	3170
72.191.28	6.70	16800	.20	5.95	10000	3070
72.191.32	6.40	17010	.18	5.90	9000	3050
72.191.36	6.60	17050	.19	6.11	10000	3050
72.191.37	7.50	15950	.22	5.73	9000	3110
72.191.42	6.40	15990	.19	6.00	9000	2930
MEAN	6.73	16938	.198	5.997	9556	3122
STD. DEV.	.42	746	.0118	.2553	527	132
CO OF VA %	6.26	4.39	5.93	4.26	5.52	4.23

† See table 63 to convert to SI metric units.

Table 39.—Compressive stress-strain tests of (70-30) MMA-TMPTMA impregnated
6- by 12-inch cylinders after 6 months' exposure at 250°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.191.2	6.90	13440†	.22	4.85†	8000†	3890
72.191.10	6.40	14470	.20	5.26	8000	3290
72.191.13	6.10	15170	.20	5.20	8000	3530
72.191.17	6.60	14250	.19	4.97	9000	3100
72.191.19	6.90	13660	.20	5.04	7000	3340
72.191.20	7.50	13090	.20	4.80	8000	3200
72.191.30	6.10	13510	.20	5.21	7000	3040
72.191.33	6.70	12940	.20	5.09	6000	3010
72.191.34	7.20	13650	.22	5.17	8000	3290
72.191.40	6.90	14960	.22	5.51	9000	3190
MEAN	6.73	13935	.205	5.111	7800	3288
STD. DEV.	.45	756	.0113	.1617	919	261
CO OF VA %	6.68	5.44	5.54	3.16	11.78	7.95

† See table 63 to convert to SI metric units.

Table 40.—Compressive stress-strain tests of (70-30) MMA-TMPTMA impregnated
6- by 12-inch cylinders after 6 months' exposure at 290°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.191.3	6.90	10960†	.13	3.73†	7000†	3200
72.191.6	5.90	13090	.09	4.04	10000	3660
72.191.7	6.60	10930				
72.191.8	6.70	10610	.11	4.00	7500	2760
72.191.11	7.70	11280				
72.191.21	6.90	10680				
72.191.27	7.20	10820	.08	3.24	7000	3900
72.191.29	6.10	10860	.20	4.68	6000	2800
72.191.35	6.90	10310	.17	3.81	7000	3700
72.191.39	6.70	10360	.09	3.58	8000	3080
MEAN	6.76	11040	.124	3.866	7500	3303
STD. DEV.	.51	762	.0474	1.6984	1258	459
CO OF VA %	7.55	6.90	38.13	43.93	16.78	13.90

† See table 63 to convert to SI metric units.

Table 41.—Compressive stress-strain tests of controls for (70-30) MMA-TMPTMA impregnated 6- by 12-inch cylinders after 6 months' exposure at -10°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.262.1	.00	4920†	.17	3.27†	1600†	2580
72.262.2	.00	5220	.16	3.00	1800	1840
72.262.4	.00	5480	.18	3.49	1400	2260
72.262.11	.00	5040	.19	3.44	1800	2180
72.262.12	.00	4560	.21	3.17	1200	2220
72.262.14	.00	5460	.16	3.23	1600	2090
72.262.15	.00	5020	.23	3.58	1600	2320
72.262.16	.00	5410	.19	3.52	1400	2340
72.262.17	.00	5340	.14	3.70	1600	2330
72.262.18	.00	5020	.28	3.61	1400	1980
MEAN	.00	5148	.191	3.401	1540	2214
STD. DEV.	.00	291	.0414	.2309	190	208
CO OF VA %	.00	5.66	21.68	6.79	12.32	9.38

† See table 63 to convert to SI metric units.

Table 42.—Compressive stress-strain tests of controls for (70-30) MMA-TMPTMA impregnated 6- by 12-inch cylinders after 6 months' exposure at 70°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
73.262.3	.00	4540†	.21	3.25†	2400†	2260
73.262.6	.00	4400	.15	3.28	1800	2920
73.262.7	.00	4660	.17	3.69	1600	2290
73.262.8	.00	4420	.19	3.42	1600	2100
73.262.10	.00	4510	.29	3.37	2000	2790
73.262.28	.00	4490	.21	3.81	1400	2440
73.262.31	.00	4670	.17	3.74	2000	2300
73.262.32	.00	5110	.30	3.66	2000	2330
73.262.40	.00	4920	.19	3.63	1600	2380
73.262.44	.00	4620	.16	3.52	1800	2340
MEAN	.00	4635	.204	3.538	1820	2415
STD. DEV.	.00	224	.0515	.2101	290	250
CO OF VA %	.00	4.83	25.19	5.94	15.92	10.35

† See table 63 to convert to SI metric units.

Table 43.—Compressive stress-strain tests of controls for (70-30) MMA-TMPTMA impregnated 6- by 12-inch cylinders after 6 months' exposure at 250°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.262.20	.00	4350†	.16	2.69†	1200†	1920
72.262.21	.00	4600	.20	2.88	1400	2130
72.262.22	.00	4630	.13	2.68	1600	2760
72.262.25	.00	4630	.23	2.81	1400	2130
72.262.26	.00	4560	.19	2.88	1200	2240
72.262.27	.00	4620	.10	2.73	1600	2240
72.262.29	.00	4600	.15	2.65	1600	2160
72.262.33	.00	4620	.11	2.82	1600	2400
72.262.35	.00	3060	.16	2.84	1200	1960
72.262.36	.00	5200	.10	2.87	1400	2460
MEAN	.00	4566	.154	2.784	1420	2240
STD. DEV.	.00	328	.0445	.0849	175	249
CO OF VA %	.00	7.19	28.84	3.05	12.33	11.09

† See table 63 to convert to SI metric units.

Table 44.—Compressive stress-strain tests of controls for (70-30) MMA-TMPTMA impregnated 6- by 12-inch cylinders after 6 months' exposure at 290°F

SPECIMEN NUMBER	POLYMER LOADING (WT. %)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
72.262.5	.00	4530†	.11	1.87†	1200†	3280
72.262.13	.00	4460	.12	2.30	1200	2400
72.262.19	.00	4100	.17	2.13	1200	2600
72.262.37	.00	4630	.05	2.59	1100	2440
72.262.38	.00	4280	.19	2.26	1200	2600
72.262.45	.00	4100	.26	3.28	1200	2720
72.262.41	.00	4140	.17	2.27	1200	2640
72.262.34	.00	4670	.08	1.71	1200	2600
72.262.30	.00	4140	.07	2.13	1300	2520
72.262.43	.00	4140	.13	2.98	1200	2160
MEAN	.00	4318	.135	2.352	1200	2616
STD. DEV.	.00	230	.0637	.4339	47	295
CO OF VA %	.00	5.33	47.09	18.45	3.93	11.26

† See table 63 to convert to SI metric units.

Table 45.—Compressive strength after long-term exposure at $-10^{\circ}F$

Material	Specimen No., 72.—	Exposure time, months	Compressive strength, lb/in ²
Unimpregnated concrete	263.1	14	5,500 [†]
	.7	14	5,800
	.9	14	5,700
	.10	14	5,700
	.11	14	5,600
(60-40)	201.2	14	17,900
S-TMPTMA impregnated concrete	.3	14	17,600
	.5	14	19,500
	.20	14	20,000
	.35	14	19,600
(70-30)	192.8	17	17,300
MMA-TMPTMA	.12	17	17,500
impregnated concrete	.27	17	16,300
	.29	17	19,200
	.39	17	17,400

6- by 12-inch cylinders.

[†] See table 63 to convert to SI metric units.

Table 46.—Effect of exposure time and temperature on compressive strength and modulus of elasticity of unimpregnated and (70-30) MMA-TMPTMA impregnated concrete 6- by 12-inch cylinders

Task	Temperature, °F °C		Exposure time	Polymer loading, wt %	Ultimate strength, lb/in ²	Modulus of elasticity, 10 ⁶ lb/in ²
72.191	-10	-23	6 month	6.78	17,180 [†]	5.96 [†]
72.194	-10	-23	24 hour	6.43	18,100	5.94
72.262	-10	-23	6 month	0	5,150	3.40
72.260	-10	-23	24 hour	0	5,960	3.75
72.191	70	21	6 month	6.73	16,990	6.00
72.194	70	21	24 hour	6.46	17,940	6.13
72.262	70	21	6 month	0	4,640	3.54
72.260	70	21	24 hour	0	4,280	3.40
72.191	250	121	6 month	6.73	13,940	5.11
72.194	250	121	24 hour	6.36	12,840	5.17
72.262	250	121	6 month	0	4,570	3.05
72.260	250	121	24 hour	0	4,570	2.87
72.191	290	143	6 month	6.76	11,040	3.87
72.194	290	143	24 hour	6.40	12,260	4.31
72.262	290	143	6 month	0	4,320	2.35
72.260	290	143	24 hour	0	4,790	2.65

[†] See table 63 to convert to SI metric units.

Table 47.—Strength and elasticity tests at -10°F of unimpregnated concrete 6- by 12-inch cylinders, controls for (70-30) MMA-TMPTMA and (60-40) styrene-TMPTMA impregnated cylinders

SPECIMEN NUMBER	TEMP. DEG. F (C)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
73.260.1	-10(-23)	6000†	.19	3.56†	1300†	3000
73.260.2	-10(-23)	5890	.19	3.69	1400	2570
73.260.3	-10(-23)	5960	.22	3.66	1400	2540
73.260.4	-10(-23)	6020	.18	3.97	1500	2130
73.260.5	-10(-23)	6370	.20	3.96	1400	2640
73.260.6	-10(-23)	5930	.17	3.58	1200	2580
73.260.7	-10(-23)	5990	.22	3.58	1400	2740
73.260.8	-10(-23)	5730	.18	3.77	2400	2340
73.260.9	-10(-23)	5820	.16	3.73	1300	2180
73.260.10	-10(-23)	5840	.19	3.99	1500	2450
MEAN		5956	.189	3.747	1480	2517
STD. DEV.		171	.0202	.1686	336	259
COEF. VAR. (%)		2.88	10.67	4.50	22.70	10.30

† See table 63 to convert to SI metric units.

Table 48.—Strength and elasticity tests at 70°F of unimpregnated concrete 6- by 12-inch cylinders, controls for (70-30) MMA-TMPTMA and (60-40) styrene-TMPTMA impregnated cylinders

SPECIMEN NUMBER	TEMP. DEG. F (C)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
73.260.11	70(21)	3980†	.21	3.61†	1300†	1860
73.260.13	70(21)	4490	.18	3.54	1200	2000
73.260.14	70(21)	3980	.16	3.54	1400	1680
73.260.15	70(21)	4470	.16	3.25	2500	2740
73.260.16	70(21)	4460	.21	3.04	1200	2460
MEAN		4276	.186	3.401	1520	2152
STD. DEV.		271	.0237	.2467	554	443
COEF. VAR. (%)		6.35	12.74	7.25	36.45	20.58

† See table 63 to convert to SI metric units.

Table 49.—Strength and elasticity tests at 250°F of unimpregnated concrete 6- by 12-inch cylinders, controls for (70-30) MMA-TMPTMA and (60-40) styrene-TMPTMA impregnated cylinders

SPECIMEN NUMBER	TEMP. DEG. F (C)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
73.260.17	250 (121)	4630†	.16	3.16†	1200†	2220
73.260.18	250 (121)	4420	.08	2.55	1600	2400
73.260.21	250 (121)	4440	.12	2.86	1600	2060
73.260.22	250 (121)	4770	.14	2.90	1400	2500
MEAN		4567	.123	2.867	1450	2320
STD. DEV.		169	.0348	.2492	191	233
COEF. VAR. (%)		3.69	28.18	8.69	13.21	10.03

† See table 63 to convert to SI metric units.

Table 50.—Strength and elasticity tests at 290°F of unimpregnated concrete 6- by 12-inch cylinders, controls for (70-30) MMA-TMPTMA and (60-40) styrene-TMPTMA impregnated cylinders

SPECIMEN NUMBER	TEMP. DEG. F (C)	ULTIMATE STRENGTH (PSI)	POISSON'S RATIO	ELASTIC MODULUS (MILLION PSI)	ELASTIC LIMIT (PSI)	ULTIMATE STRAIN (MICRO IN/IN)
73.260.23	290 (143)	4570†	.11	2.74†	2000†	2280
73.260.24	290 (143)	4300	.10	2.39	1400	2580
73.260.25	290 (143)	4630	.11	2.70	1600	2660
73.260.26	290 (143)	3780	.11	2.65	1800	2000
73.260.27	290 (143)	4790	.12	2.74	1200	2940
MEAN		4416	.111	2.646	1600	2492
STD. DEV.		396	.0067	.1454	316	362
COEF. VAR. (%)		8.96	6.06	5.50	19.76	14.52

† See table 63 to convert to SI metric units.

Table 51.—Multitemperature short-term tensile splitting strength,
test temperature -10°F (-23°C)

Specimen No.	Polymer loading*, wt %	Tensile splitting strength, lb/in ²	Mean, lb/in ²	Standard deviation, lb/in ²
72.208.2	5.6	1,010 [†]		
.5	6.1	1,080		
.9	5.7	970		
.10	5.9	960		
.12	6.2	1,050	1,015** [†]	59
.17	5.9	930		
.19	6.2	1,110		
.20	5.9	1,030		
.21	6.2	1,050		
.26	6.2	960		

* Monomer is (60-40) S-TMPTMA.

** Design Value = Mean - Standard Deviation = 956.

[†] See table 63 to convert to SI metric units.

Table 52.—Multitemperature short-term tensile splitting strength,
test temperature 70°F (21°C)

Specimen No.	Polymer loading*, wt %	Tensile splitting strength, lb/in ²	Mean, lb/in ²	Standard deviation, lb/in ²
72.208.1	5.9	920 [†]		
.8	6.1	1,010		
.13	5.9	1,020	940** [†]	119
.18	6.4	1,010		
.22	6.2	740		

* Monomer is (60-40) S-TMPTMA.

** Design Value = Mean - Standard Deviation = 821.

[†] See table 63 to convert to SI metric units.

Table 53.—*Multitemperature short-term tensile splitting strength,
test temperature 250°F (121°C)*

Specimen No.	Polymer loading*, wt %	Tensile splitting strength, lb/in ²	Mean, lb/in ²	Standard deviation, lb/in ²
72.208.3	5.9	1,240 [†]		
.11	6.0	960	1,006** [†]	132
.14	5.9	960		
.23	6.2	920		
.27	6.4	950		

* Monomer is (60-40) S-TMPTMA.

** Design Value = Mean - Standard Deviation = 874.

[†] See table 63 to convert to SI metric units.

Table 54.—*Multitemperature short-term tensile splitting strength,
test temperature 290°F (143°C)*

Specimen No.	Polymer loading*, wt %	Tensile splitting strength, lb/in ²	Mean, lb/in ²	Standard deviation, lb/in ²
72.208.6	5.9	560 [†]		
.15	6.2	810	770** [†]	149+
.16	5.9	920		
.24	5.9	680		
.25	6.2	880		

* Monomer is (60-40) S-TMPTMA.

** Design Value = Mean - Standard Deviation = 621.

+ Coefficient of variation is greater than 15%.

[†] See table 63 to convert to SI metric units.

Table 55.—Compressive strength, pulse velocity, specific gravity, and unit weight—
Polymer-impregnated concrete exposed to brine, brine/vapor, and vapor at 250°F (121°C)

Exposure condition	Specimen No.	Polymer loading, wt %	Initial measurements			Exposure time, yrs	Measurements after exposure			
			Specific gravity	Pulse velocity ft/s	Unit weight, lb/ft ³		Specific gravity	Pulse velocity ft/s	Compressive strength, lb/in ²	Unit weight, lb/ft ³
(60-40) Styrene-THPTMA Impregnated Concrete										
Brine	CP-5	6.9	2.36	16,205 ¹	146.76 ¹	2	2.38	14,742 ¹	10,000 ¹	148.12 ¹
Brine	CP-201	6.5	2.37	17,050	147.58	2	2.42	15,199	12,320	150.70
Brine	CP-211	6.2	2.39	17,350	148.60	2	2.44	14,824	12,210	151.74
Average		6.5	2.37	16,868	147.64		2.41	14,932	11,843	150.19
Brine-Vapor	CP-41	6.3	2.36	16,905	145.87	2	2.41	14,417	10,570	150.30
Brine-Vapor	CP-209	6.3	2.35	17,645	146.55	2	2.41	13,808	10,430	150.30
Brine-Vapor	CP-218	6.7	2.38	17,350	148.38	2	2.43	14,632	10,310	150.12
Average		6.5	2.35	17,306	146.90		2.41	14,285	11,403	150.26
Vapor	CP-8	6.8	2.35	17,050	146.55	2	2.41	15,199	11,860	149.93
Vapor	CP-213	7.0	2.36	16,475	147.07	2	2.42	14,632	11,360	150.45
Vapor	CP-222	7.0	2.44	17,028	147.07	2	2.40	14,632	10,930	149.62
Average		6.9	2.35	16,858	146.90		2.41	14,821	11,380	150.02
(70-30) MMA-THPTMA Impregnated Concrete										
Brine	123.85	5.3	2.48	17,350	146.71	1	2.46	15,199	11,890	151.29
Brine	123.35	5.1	2.41	16,340	150.43	1	2.46	14,742	11,360	150.17
Brine	123.74	5.6	2.49	16,620	148.71	1	2.46	14,967	10,290	151.05
Brine	123.66	5.8	2.40	16,200	149.21	1	2.44	14,854	11,000	152.20
Brine	123.26	6.1	2.37	15,940	147.71	1	2.43	14,524	11,790	151.29
Brine	123.07	6.2	2.37	16,760	147.89	1	2.42	14,524	11,210	150.64
Brine	123.20	6.4	2.38	16,340	147.80	1	2.43	14,003	11,070	150.17
Average		5.8	2.38	16,507	148.55		2.44	14,686	11,316	151.82
Brine-Vapor	123.22	5.3	2.41	16,205	150.22	1	2.47	14,208	11,680	153.97
Brine-Vapor	123.14	5.3	2.40	16,340	149.72	1	2.46	14,106	12,860	153.21
Brine-Vapor	123.68	5.8	2.40	16,760	149.21	1	2.45	14,967	5,600	152.57
Brine-Vapor	123.27	6.1	2.35	16,340	146.70	1	2.42	14,106	11,640	150.79
Brine-Vapor	123.31	6.1	2.37	16,480	147.71	1	2.43	14,208	11,930	151.66
Brine-Vapor	123.11	6.2	2.35	16,620	146.20	1	2.42	14,312	12,250	150.54
Brine-Vapor	123.29	6.4	2.38	16,020	149.07	1	2.42	14,526	10,220	151.06
Average		5.9	2.37	16,402	147.97		2.44	14,347	10,887	151.97
Vapor	123.41	5.3	2.40	16,480	149.72	1	2.45	14,524	12,290	152.85
Vapor	123.89	5.3	2.42	16,620	151.15	1	2.46	14,854	12,040	153.20
Vapor	123.71	5.8	2.40	16,480	149.41	1	2.45	15,082	11,860	152.57
Vapor	123.32	6.1	2.38	16,070	148.40	1	2.43	14,417	10,610	151.55
Vapor	123.33	6.1	2.35	16,070	146.70	1	2.42	14,417	12,290	150.79
Vapor	123.55	6.2	2.37	16,340	147.89	1	2.42	14,417	10,000	150.79
Vapor	123.80	6.4	2.38	16,760	149.40	1	2.43	14,742	11,460	151.30
Average		5.9	2.38	16,402	148.81		2.44	14,636	11,507	151.86
Unimpregnated Concrete										
Brine	CP-113	-	2.36	14,200	146.04	2	2.36	14,005	5,210	146.90
Brine	CP-120	-	2.33	14,500	144.86	2	2.35	13,248	5,440	146.30
Brine	CP-75	-	2.37	14,100	143.39	2	2.32	12,650	4,660	144.33
Average		-	2.31	14,268	144.16		2.36	13,301	5,063	145.93
Brine-Vapor	CP-118	-	2.33	14,900	145.02	2	2.40	13,808	5,210	149.26
Brine-Vapor	CP-126	-	2.35	14,500	146.37	2	2.40	13,338	4,290	149.11
Brine-Vapor	CP-103	-	2.38	14,200	145.96	2	2.38	13,722	5,080	146.41
Average		-	2.31	14,533	144.11		2.38	13,293	4,833	148.29
Vapor	CP-178	-	2.30	14,300	143.34	2	2.36	13,711	7,790	147.35
Vapor	CP-119	-	2.36	14,300	147.06	2	2.40	14,005	6,890	149.46
Vapor	CP-81	-	2.31	14,200	144.16	2	2.38	13,711	6,210	148.06
Average		-	2.32	14,266	144.83		2.38	13,809	7,630	148.29

6- by 12-inch cylindrical specimens: Specific gravity and pulse velocity measurements are made at room temperature; compressive strength tests are made at 121°C (250°F) test temperature.
¹See table 63 to convert to SI metric units.

Table 56.—Compressive strength, pulse velocity, specific gravity, and unit weight—
Styrene-TMPTMA impregnated concrete exposed to brine, brine/vapor, and vapor at 290°F (143°C)

Exposure condition	Specimen No.	Polymer loading, wt %	Initial measurements			Exposure time, years	Measurements after exposure			Unit weight, lb/ft ³
			Specific gravity	Pulse velocity, ft/s	Unit weight, lb/ft ³		Specific gravity	Pulse velocity, ft/s	Compressive strength, lb/in ²	
(60-40) Styrene-TMPTMA Impregnated Concrete										
Brine	OSW-355	6.7	2.36	16,760†	147.07†	2	2.41	14,417†	10,460†	150.19†
Brine	OSV-258	5.7	2.40	16,760	149.62	2	2.44	14,312	10,820	151.78
Brine	OSW-356	5.6	2.25	16,800	148.60	2	2.63	15,241	9,790	151.63
Brine	Average	6.0	2.38	16,806	148.43		2.43	14,890	10,357	151.20
Brine-Vapor	OSW-340	6.4	2.37	16,760	147.58	2	2.41	14,967	11,640	150.08
Brine-Vapor	OSW-333	5.9	2.39	16,760	149.11	2	2.43	15,561	10,000	151.62
Brine-Vapor	OSW-236	5.6	2.42	16,820	150.64	2	2.63	15,318	11,070	151.42
Brine-Vapor	Average	6.0	2.39	16,713	149.11		2.42	15,282	10,963	151.04
Vapor	OSW-295	5.9	2.37	17,200	147.89	2	2.42	15,318	10,570	150.64
Vapor	OSW-371	5.9	2.39	17,050	148.60	2	2.42	16,742	9,960	151.26
Vapor	OSW-270	5.8	2.35	17,050	148.60	2	2.62	15,254	10,610	150.49
Vapor	Average	5.8	2.38	17,100	148.36		2.42	15,207	11,080	150.80
Unimpregnated Concrete										
Brine	199.2.1	-	2.34	14,635	145.53	1	2.31	12,815	6,250	145.84
Brine	199.2.2	-	2.32	14,420	144.49	1	2.31	11,883	5,820	144.19
Brine	199.2.3	-	2.31	14,110	144.19	1	2.32	12,815	6,790	144.35
Brine	199.2.4	-	2.31	14,110	144.19	1	2.32	12,331	7,090	145.28
Brine	Average	-	2.32	14,318	144.65		2.32	12,441	6,465	144.41
Brine-Vapor	199.2.5	-	2.30	14,525	143.54	1	2.31	12,985	7,820	143.76
Brine-Vapor	199.2.6	-	2.30	14,525	143.04	1	2.31	13,430	8,070	143.76
Brine-Vapor	199.2.7	-	2.29	14,525	142.69	1	2.35	12,549	6,860	146.50
Brine-Vapor	199.2.8	-	2.21	14,525	143.69	1	2.32	12,985	8,790	146.63
Brine-Vapor	Average	-	2.30	14,525	143.24		2.32	12,992	7,360	144.61
Vapor	199.2.9	-	2.35	14,005	146.20	1	2.42	14,208	6,930	150.47
Vapor	199.2.10	-	2.35	14,420	146.37	1	2.35	14,524	9,210	146.47
Vapor	199.2.11	-	2.31	14,210	144.04	1	2.35	13,808	9,000	146.37
Vapor	199.2.12	-	2.34	14,210	145.87	1	2.34	14,534	8,070	145.52
Vapor	Average	-	2.34	14,211	145.62		2.36	14,266	8,303	147.21

6- by 12-inch cylindrical specimens: Specific gravity and pulse velocity measurements are made at room temperature; compressive strength is made at 143°C (290°F) test temperature.

†See table 63 to convert to SI metric units.

Table 57.—Changes in weight, length, and resonant frequency—
Polymer-impregnated concrete exposed to brine, brine/vapor, and vapor at 250°F (121°C)

Exposure time	Specimen No.	Polymer loading, wt %	Weight change, %	Length change, mm/in	Resonant frequency		Change percent	
					$f^2 \times 10^3$ cps, Initial	After exposure		
(60-40) Styrene-TMPTMA Impregnated Concrete								
Brine	6 months	CPE-47, CPI-45	6.0	+0.3	+ 276†	570†	563†	- 1.2
Brine	1 year	CPE-47, CPI-45	6.0	+0.4	+ 488	570	533	- 6.5
Brine	2 years	CPE-47, CPI-45	6.0	+1.0	+ 789	570	497	-12.8
Brine-Vapor	6 months	CPE-55, CPI-48	6.0	+1.0	+ 404	573	480	-16.2
Brine-Vapor	1 year	CPE-55, CPI-48	6.0	+0.8	+ 525	573	456	-20.4
Brine-Vapor	2 years	CPE-55, CPI-48	6.0	+1.4	+ 714	573	518	- 9.6
Vapor	6 months	CPE-60, CPI-49	6.1	+0.8	+ 290	570	563	- 1.2
Vapor	1 year	CPE-60, CPI-49	6.1	+1.1	+ 558	570	540	- 5.3
Vapor	2 years	CPE-60, CPI-49	6.1	+1.7	+ 819	570	518	- 9.1
(70-30) MMA-TMPTMA Impregnated Concrete								
Brine	6 months	124.18, 124.4	5.6	+1.3	+ 704	558	540	- 3.2
Brine	1 year	124.18, 124.4	5.6	+1.4	+ 951	558	476	-14.7
Brine-Vapor	6 months	124.1, 124.21	5.5	+1.6	+ 614	555	533	- 4.0
Brine-Vapor	1 year	124.1, 124.21	5.5	+1.9	+1,015	555	497	-10.5
Vapor	6 months	124.3, 124.8	5.6	+1.6	+ 703	558	547	- 2.0
Vapor	1 year	124.3, 124.8	5.6	+1.6	+ 987	558	500	-10.4
Unimpregnated Concrete								
Brine	6 months	CP-64, CP-44	none	+2.3	+ 717	397	378	- 0.4
Brine	1 year	CP-64, CP-44	none	+1.9	+ 674	397	382	- 0.4
Brine	2 years	CP-64, CP-44	none	+0.9	+ 913	397	360	- 0.9
Brine-Vapor	6 months	CPE-41, CPE-42	none	+2.8	+ 706	403	384	- 4.7
Brine-Vapor	1 year	CPE-41, CPE-42*	none	+1.8	+ 488	403	384	- 4.7
Brine-Vapor	2 years	CPE-41, CPE-42*	none		+ 794	403	416	+ 3.2
Vapor	6 months	CPE-43, CPE-46	none	+2.0	+ 358	397	413	+ 4.0
Vapor	1 year	CPE-43, CPE-46	none	+1.9	+ 363	397	429	+ 8.1
Vapor	2 years	CPE-43, CPE-46	none	+1.3	+ 394	397	476	+19.9

Results are average values of two 4- by 4- by 30-inch specimens.

*One bar only (Specimen No. CPE-42).

f = frequency

†See table 63 to convert to SI metric units.

Table 58.—Changes in weight, length, and resonant frequency—
Polymer-impregnated concrete exposed to brine, brine/vapor, and vapor at 290°F (143°C)

Exposure time	Specimen No.	Polymer loading, wt %	Weight change, %	Length change, in/in	Resonant frequency		Change percent
					$f^2 \times 10^3$ cps		
					Initial	After exposure	
(60-60) Styrene-MPTMA Impregnated Concrete							
Brine 6 months	106, 119	5.4	+0.3	+ 791†	656†	565†	-13.8
Brine 1 year	106, 119	5.4	+0.3	+1,287	656	532	-18.8
Brine 2 years	106, 119	5.4	+0.8	+1,528	656	500	-23.8
Brine-Vapor 6 months	111, 118	5.6	+1.4	+ 694	619	540	-12.8
Brine-Vapor 1 year	111, 118	5.6	+1.4	+1,255	619	504	-18.6
Brine-Vapor 2 years	111, 118	5.6	+1.6	+1,692	619	494	-20.2
Vapor 6 months	110, 112	5.6	+1.6	+ 719	632	547	-13.4
Vapor 1 year	110, 112	5.6	+1.7	+1,266	632	518	-18.0
Vapor 2 years	110, 112	5.6	+2.1	+1,509	632	522	-17.4
(70-30) MMA-TMPTMA Impregnated Concrete							
Brine 6 months	126.11, 126.12	5.8	+2.1	+1,753	555	412	-25.7
Brine 1 year	126.11, 126.12	5.8	-	-	555	-	-
Brine-Vapor 6 months	126.2, 126.19	5.8	+2.2	+1,687	570	425	-25.4
Brine-Vapor 1 year	126.2, 126.19	5.8	-	-	570	-	-
Vapor 6 months	126.16, 126.17	5.7	+1.3	+1,433	565	467	-15.8
Vapor 1 year	126.16, 126.17	5.7	-	+3,085*	565	368*	-36.9*
Unimpregnated Concrete							
Brine 6 months	200.7, 200.8	none	+1.9	+ 612	393	333	-15.3
Brine 1 year	200.7, 200.8	none	-1.8	+ 756	393	288	-26.7
Brine-Vapor 6 months	200.9, 200.10	none	+1.8	+ 551	403	336	-16.6
Brine-Vapor 1 year	200.9, 200.10	none	-2.1	+ 663	403	270	-33.0
Vapor 6 months	200.11, 200.12	none	-0.9	+ 219	403	391	- 3.1
Vapor 1 year	200.11, 200.12	none	-2.2	+ 335	403	406	+ 0.7

Results are average values of two 4- by 4- by 30-inch specimens.

*One bar only (Specimen No. 126.17).

f = frequency

See table 63 to convert to SI metric units.

Table 59.—Flexure strength after exposure to brine, brine/vapor, and vapor at 250°F (121°C)

Exposure condition	Specimen No.	Polymer loading, wt %	Ultimate load, lbs	Modulus of rupture, lb/in ²	Exposure time, yrs
(60-40) Styrene-THPTMA Impregnated Concrete					
Brine	CPE-47	6.5	5,100 [†]	956 [†]	2
Brine	CPI-45	5.4	6,520	1,223	2
Brine	CPI-42	5.1	6,160	1,155	2
	Average	5.7	5,926	1,111	
Brine-Vapor	CPE-55	6.1	6,340	1,189	2
Brine-Vapor	CPI-48	5.8	6,220	1,166	2
Brine-Vapor	CPI-43	5.0	6,720	1,260	2
	Average	5.6	6,426	1,205	
Vapor	CPE-60	6.4	4,480	840	2
Vapor	CPI-49	5.6	5,160	967	2
Vapor	CPI-44	4.9	5,720	1,072	2
	Average	5.6	5,120	960	
(70-30) MMA-THPTMA Impregnated Concrete					
Brine	124.18	5.9	7,300	1,369	1
Brine	124.4	5.2	5,800	1,087	1
Brine	124.20	5.4	6,760	1,284	1
	Average	5.5	6,613	1,240	
Brine-Vapor	124.1	5.8	5,960	1,117	1
Brine-Vapor	124.21	5.2	5,840	1,095	1
Brine-Vapor	124.2	5.4	8,200	1,537	1
	Average	5.5	6,666	1,250	
Vapor	124.3	5.9	6,540	1,226	1
Vapor	124.8	5.2	6,360	1,193	1
Vapor	124.9	5.4	5,280	990	1
	Average	5.5	6,060	1,136	
Unimpregnated Concrete					
Brine	CPE-24	-	3,100	581	2
Brine	CPE-64	-	2,900	544	2
Brine	CPE-44	-	3,640	695	2
	Average	-	2,880	540	
Brine-Vapor	CPE-42	-	3,520	660	2
Brine-Vapor	CPE-23	-	3,260	611	2
Brine-Vapor	-	-	-	-	2
	Average	-	3,390	635	
Vapor	CPE-43	-	4,720	885	2
Vapor	CPE-25	-	4,000	750	2
Vapor	CPE-46	-	3,840	720	2
	Average	-	4,186	785	

4- by 4- by 30-inch bars tested at room temperature.
[†]See table 63 to convert to SI metric units.

Table 60.—Flexure strength after exposure to brine, brine/vapor, and vapor at 290°F (143°C)

Exposure condition	Specimen No.	Polymer loading, wt %	Ultimate load, lbs	Modulus of rupture, lb/in ²	Exposure time, yrs
(60-40) Styrene-THPTMA Impregnated Concrete					
Brine	106	5.7	5,660 [†]	1,061 [†]	2
Brine	119	5.2	4,900	918	2
	Average	5.4	5,280	989	
Brine-Vapor	111	5.7	5,000	937	2
Brine-Vapor	118	5.4	4,560	855	
	Average	5.6	4,780	896	
Vapor	112	5.6	4,840	907	2
Vapor	110	5.7	5,860	1,099	2
	Average	5.6	5,350	1,003	
Unimpregnated Concrete					
Brine	200.7	-	3,200	600	1
Brine	200.8	-	3,120	585	1
Brine	200.14	-	3,460	649	1
	Average	-	3,260	611	
Brine-Vapor	200.9	-	3,300	619	1
Brine-Vapor	200.10	-	3,000	563	1
Brine-Vapor	200.16	-	3,020	566	1
	Average	-	3,106	583	
Vapor	200.11	-	4,340	814	1
Vapor	200.12	-	3,760	705	1
Vapor	200.18	-	4,000	750	1
	Average	-	4,033	756	

4- by 4- by 30-inch bars tested at room temperature.
[†]See table 63 to convert to SI metric units.

Table 61.—*Neutron and gamma ray moisture and density determination*

Condition of concrete	Neutron and gamma ray measurements					
	Gravimetric measurements		Position No. 1		Position No. 2	
	Density, lb/ft ³	Weight of moisture or polymer, lb/ft ³	Density, lb/ft ³	Weight of moisture of polymer, lb/ft ³	Density, lb/ft ³	Weight of moisture or polymer, lb/ft ³
Air dry	146.5†	8.5†	131.5†	6.0†	130.0†	6.2†
Oven dry	138.0	0	122.5	1.4	117.5	1.4
Surface polymerized	139.6	1.6	122.5	4.3	121.0	4.2

† See table 63 to convert to SI metric units.

Table 62.—Resistance to sulfate attack, polymer-impregnated concrete drain tile

Class of pipe	Monomer	Polymer loading, %	Sample No.	Immersion test		Accelerated test	
				Test day	Expansion %	Test cycle	Expansion %
PQ	None	—	A1	1,092	0.317	361	² 0.536
PQ	None	—	B1	1,092	.221	615	² .500
AQ	None	—	A2	1,092	.223	300	² .580
AQ	None	—	B2	1,092	.099	300	² .634
HQ	None	—	A3	1,092	.075	1,092	.036
HQ	None	—	B3	1,092	.091	1,092	.516
PQ	MMA	7.4	1-5	549	² .538	225	² .536
PQ	ES	9.5	1-12	1,092	.226	1,092	.064
AQ	MMA	7.1	2-3	1,092	.328	1,092	¹ .205
AQ	ES	8.6	2-13	1,092	.264	1,092	.160
HQ	MMA	6.6	3-2	1,092	.402	1,092	¹ .366
HQ	ES	5.8	3-19	1,092	.105	1,092	.106

PQ = poor quality

AQ = average quality

HQ = high quality

MMA = methyl methacrylate

EP-S = epoxy-styrene

Specimens cut from 4-inch-diameter drain tile to approximately 1- by 1- by 6-inch size.

Specimens oven-dried at 150°C (302°F) prior to impregnation and radiation polymerized.

Values for expansion are averages of three specimens, except as noted:

¹ Average net expansion of two specimens — one specimen removed from test for examination.

² Removal from test; expansion exceeded 0.5%.

Immersion test = continuous soaking in 10% Na₂SO₄ solution.

Accelerated test = soaking in 2.1% Na₂SO₄ solution at 22°C (73°F) and drying at 54°C (130°F); one cycle per day.

Table 63.—SI metric conversion factors

To Convert From	To	Multiply By
inch (in)	millimetre (mm)	25.4000*
inch (in)	metre (m)	0.0254*
pounds/square inch (lb/in ²)	gigapascals (GPa)	6.895×10^{-6}
pounds/square inch (lb/in ²)	megapascals (MPa)	6.895×10^{-3}
degree Fahrenheit (°F)	degree Celsius (°C)	$^{\circ}\text{C} = (^{\circ}\text{F} - 32)/1.8$
feet/second (ft/s)	metres/second (m/s)	0.3048*
pounds/cubic yard (lb/yd ³)	kilograms/cubic metre (kg/m ³)	0.5933
pounds/cubic foot (lb/ft ³)	kilograms/cubic foot (kg/ft ³)	16.018
pounds (lb)	kilograms (kg)	0.45359
inch-pounds (in-lb)	Newton meter (N·m)	0.11298
foot (ft)	millimetres (mm)	30.48*
centipoise (cP)	pascal-second (Pa·s)	0.001*
cycles per second (cps)	hertz (hz)	1.00*

* Exact figure

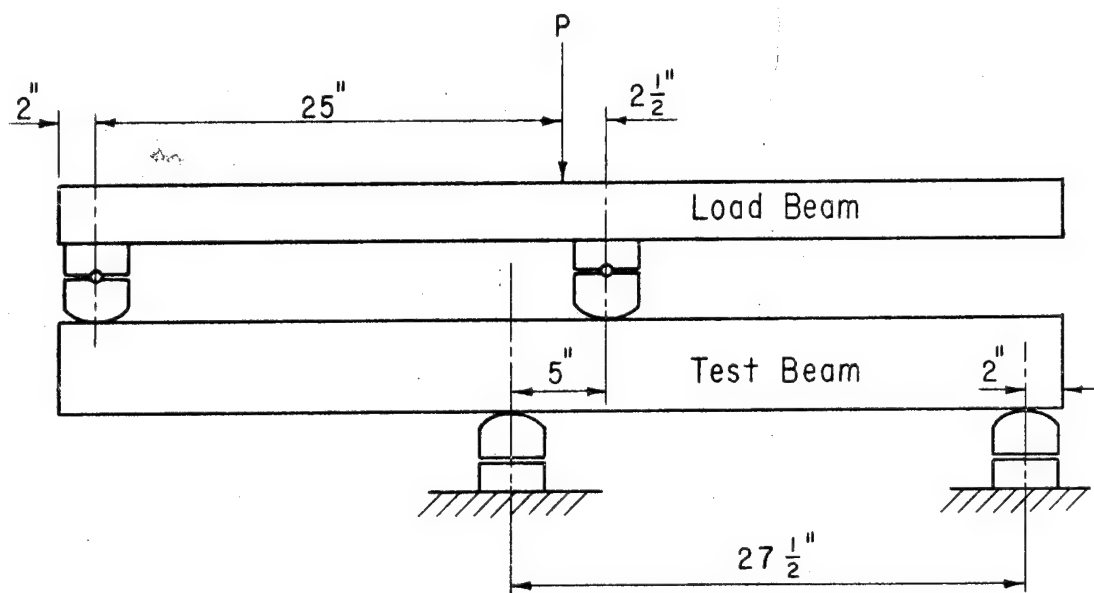
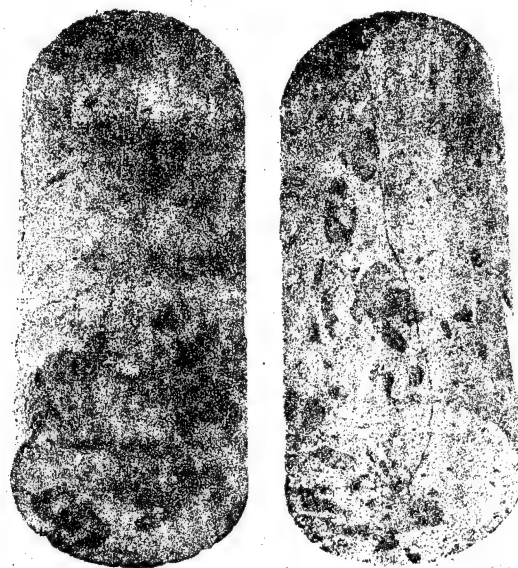


Figure 1.—Schematic diagram of flexure test setup.



72.65.8
Monomer PMMA
partial impregnation,
1/2" depth
expanded shale
aggregate

72.65.15
Polyester/styrene
partial impregnation
1/2" depth
expanded shale
aggregate

Figure 2.—Cracking of partially-impregnated expanded shale specimens. (C-8350-1) Photo P801-D-77359

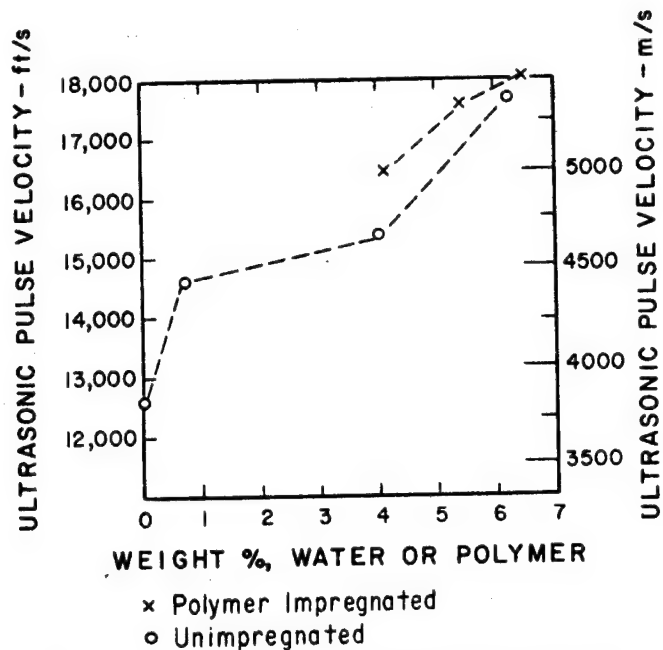


Figure 3.—Ultrasonic pulse velocity of 3- by 6-inch (76- by 152-mm) specimens.

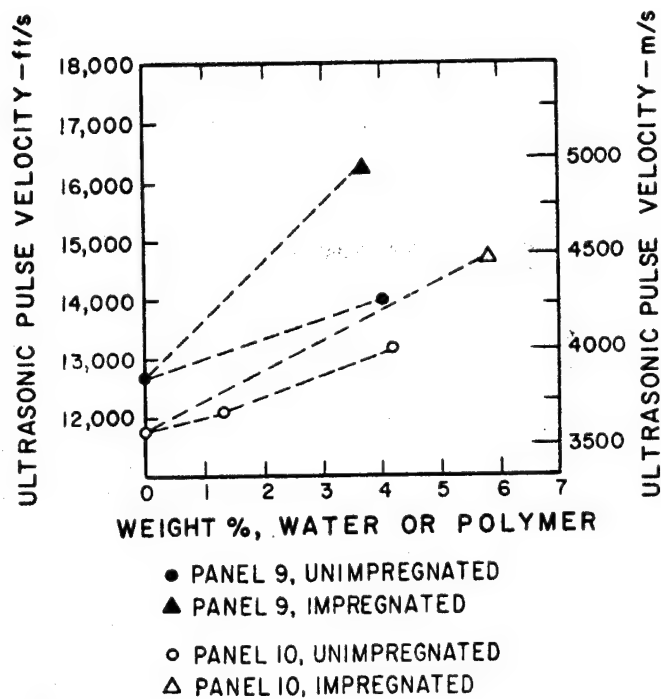


Figure 4.—Ultrasonic pulse velocity of prestressed bridge deck panels.

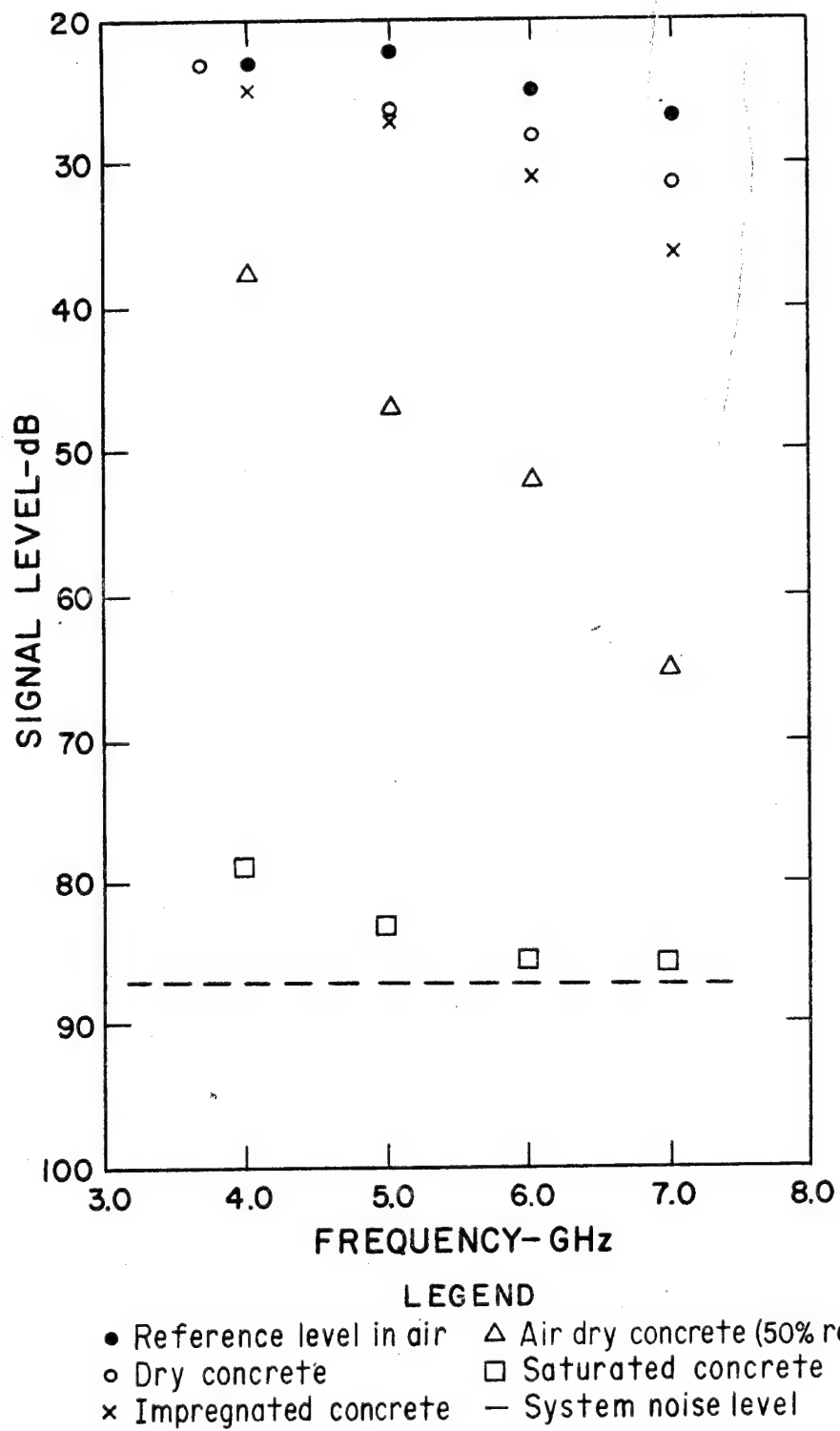


Figure 5.—Microwave test of polymer-impregnated concrete.

APPENDIX

MEMORANDUM TO CHIEF, CONCRETE AND STRUCTURAL BRANCH, dated June 26, 1974
"EXAMINATION OF POLYMER-IMPREGNATED CONCRETE AFTER EXPOSURE
IN BRINE AND VAPOR AT 250° AND 290°F."

UNITED STATES GOVERNMENT

Memorandum

TO : Memorandum
Chief, Concrete and Structural Branch 9R4 7123
Attention: 1512

FROM : Chief, Applied Sciences Branch

SUBJECT: Examination and testing of polymer-impregnated concrete after exposure in brine and vapor at 250° F and 290° F

Denver, Colorado
DATE: June 26, 1974

Applied Sciences Referral No. 74-3-6

Investigations by: Physical Sciences and Water Treatment Section,
T. E. Backstrom, Head, D. M. Hopkins, E. F. Monk, and C. A. Bechtold,
investigators

INTRODUCTION

Concrete specimens were impregnated with 70 percent methyl methacrylate (MMA), 30 percent trimethylopropane trimethacrylate (TMPTMA), and 60 percent styrene - 40 percent TMPTMA. These comonomer impregnated specimens were cured thermal catalytically using alpha tert-butylazo, isobutyro-nitrile, and benzoyl peroxide initiators, respectively. They were then exposed in the brine loop to synthetic sea water concentrates (38,000 and 73,000 ppm) at elevated temperatures. After 1 year, the MMA-TMPTMA specimens exposed at 290° F (with corresponding 38,000-ppm brine, brine-vapor, and vapor environmental conditions) were disaggregated or, as was the case with those exposed to vapor only, deteriorated sufficiently to render compression testing impossible. Specimens of styrene-TMPTMA exposed for 2 years showed no obvious signs of deterioration and a gradual decrease in compressive strength (Figures 1A and 1B).

This report covers the examination and analysis of the concrete paste, embedded polymer, and includes the investigation of other materials related to these two systems.

Following is a list of all specimen samples and related materials examined and the investigation techniques employed:

<u>Specimen and related materials</u>	<u>Exposure</u>
1. Type II cement (nonhydrated)	None
2. Hydrated Type II cement	a. None b. 24 hours in 38,000-ppm brine
3. Concrete paste - unimpregnated	290° F vapor, 1 year
4. Concrete paste - MMA-TMPTMA impregnated	None

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5. Concrete paste - MMA-TMPTMA impregnated	290° F brine, 1 year
6. Concrete paste - MMA-TMPTMA impregnated	250° F vapor, 1 year
7. Concrete paste - MMA-TMPTMA impregnated	290° F vapor, 1 year
8. Concrete paste - styrene-TMPTMA impregnated	290° F vapor, 2 years
9. MMA-TMPTMA standard bar	a. None b. Pyrolysis
10. MMA-TMPTMA polymer fragments	a. 250° F and 290° F vapor, 1 year b. 290° F brine, 1 year
11. Styrene-TMPTMA polymer fragments	290° F vapor, 2 years
12. TMPTMA monomer	None

Investigation Techniques

1. Examination of the concrete - visually, differential thermal analysis (DTA), X-ray diffraction (XRD), and infrared absorption analysis (IR)
2. Infrared analysis on the related polymers, monomers, and polymer fragments
3. Differential thermal analysis on the related polymers

INVESTIGATION DISCUSSION

Cement paste separated from MMA-TMPTMA and styrene-TMPTMA polymer concrete specimens along with hydrated and nonhydrated Type II cement were examined by XRD and DTA. The major mineral constituents, with the exception of calcium hydroxide, usually detected in hardened portland cement concrete pastes cured at ordinary temperatures were present in similar proportions in all of the concrete pastes analyzed. Sample identification data for calcium hydroxide and calcium carbonate detection are presented in Table 1.

Review of the X-ray diffraction column in Table 1 indicates crystalline calcium hydroxide is not detectable in the concrete pastes analyzed from control and MMA-TMPTMA specimens subjected to brine loop environments at 290° F (Figure 2). X-ray analysis determines only crystalline calcium hydroxide. DTA patterns suggest the calcium hydroxide is still present in the 290° F exposed MMA-TMPTMA specimens but probably in a poorly crystallized or amorphous form (3), as DTA can detect both crystalline and noncrystalline materials. It is not understood why DTA could not detect calcium hydroxide in the unexposed and 250° F vapor exposed MMA-TMPTMA specimens or the control 290° F vapor exposed specimen. While there is still a question of its significance, it

might be noted that two of these three specimens were not exposed to above 250° F environments and the remaining specimen was an unimpregnated control exposed to 290° F vapor.

Trace amounts of calcium carbonate in samples corresponding to the calcium hydroxide data were detected by XRD. DTA analyses indicate calcium carbonate detection in the same samples with the exceptions of Type II nonhydrated cement, 290° F vapor control concrete, and the 290° F brine MMA-TMPTMA concrete. Preparation of suitable standards to determine limits of and interferences with detectability for DTA as well as XRD analyses would be necessary in any additional studies to attempt resolution of these questions.

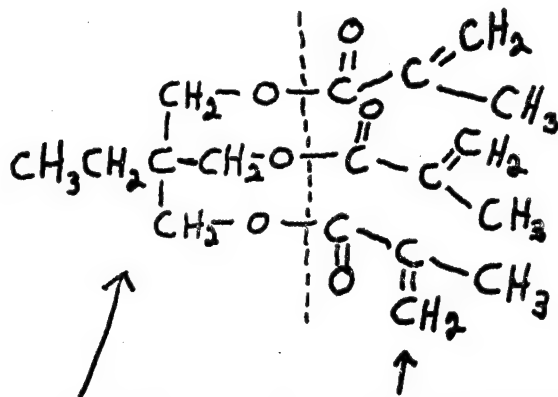
It is interesting to note, however, that DTA and XRD detected the presence of crystalline calcium hydroxide in the styrene-TMPTMA 290° F 2-year vapor-exposed specimen. This contrasts sharply with the XRD data indicating the absence of crystalline Ca(OH)_2 in 290° F exposures for both control and MMA-TMPTMA impregnated specimens, suggesting styrene-TMPTMA contributes to the retention of crystallinity for Ca(OH)_2 .

Comparison of infrared spectra for the standard MMA-TMPTMA polymer bar, polymer fragments dislodged from a 250° F exposed specimen, and the polymer fragments from 290° F exposed specimens indicates exposures up to 250° F have little or no effect on the polymer structure but beyond that, considerable change takes place (Figure 3). Spectrum No. 4 in Figure 3 also indicates the remaining polymer fragments from 290° F exposures could be either a carboxylic acid or an alcoholic derivative, or both. Attempts to dissolve this material in the usual organic solvents were fruitless, suggesting it too was a crosslinked material like its parent, the unexposed MMA-TMPTMA polymer.

DTA patterns were run on samples of the MMA-TMPTMA standard bar and styrene-TMPTMA. (The latter sample was polymer fragments dislodged from one of the exposed styrene-TMPTMA concrete specimens as no standard was provided and time considerations did not permit us to prepare our own. These polymer-concrete specimens were in such obviously good condition that the impregnated polymer was presumably unaltered.) The MMA-TMPTMA sample underwent transition at 280° C whereas the styrene-TMPTMA transition occurred at 425° C (Figure 4), indicating a higher resistance to thermal decomposition for the latter, which is consistent with its brine loop history. Although DTA temperatures for the two polymers' structural change appear extreme when compared with MMA-TMPTMA failure in the 290° F brine loop, consideration must be given to other loop environmental factors such as moisture, concrete matrix, pressure, etc.

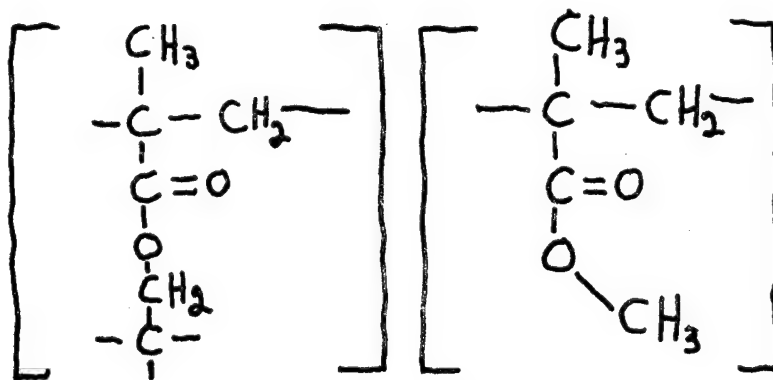
The foregoing data obtained from examination of the pure polymer samples and fragments suggested that thermal decomposition of the MMA-TMPTMA had taken place while specimens were being exposed in the 290° F

brane loop systems (Figure 5). Decomposition could then be followed or accompanied by chemical attack on the concrete paste by one or several polymer degradation products. Thermal degradation of polymeric materials has been extensively reported (1), and in some cases, their pathways can be reasonably predicted if some consideration is given to the structural formulae of monomeric and resulting polymeric materials involved in their original syntheses. The structural formula for the TMPTMA molecule depicting its functional groups is as follows:



TMP (Trimethylopropane) + 3MMA (Methyl Methacrylate) = TMPTMA

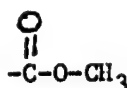
As can be seen from this formula diagram, the three methyl methacrylate portions have the olefin or vinyl functionality enabling them to participate in free radical chain polymerization reactions. In most TMPTMA polymer systems, these three functions are almost completely reacted, leaving only minimal residual vinyl character in the polymer end product. A simplified cross-sectional view of a reacted MMA plus TMPTMA monomer system (the MMA monomer would necessarily react through the MMA radical functionality of the TMPTMA monomer) can be shown as follows:



TMPTMA pendant

MMA pendant

Even in this simplified diagram, it is noticed that the methyl ester portion of the MMA pendant is not altered:



Comparison of this system with that of the styrene-TMPTMA system readily shows that no ester linkages or more specifically, methyl ester linkages, hang freely as the styrene molecule



has none. Although the TMPTMA molecule can be considered a bulky tri-ester, it is best considered a substituted tri-alcohol. Many of the reported controlled thermally induced depolymerizations have resulted in producing degradation products closely resembling the original monomeric materials which are the least altered as final polymer pendants. It would be reasonable then to hypothesize that the MMA-TMPTMA polymer would thermally decompose to products a large portion of which would contain methacrylate ester character.

Infrared spectra of the MMA and TMPTMA monomers have a very prominent absorption peak between $1,600\text{ cm}^{-1}$ and $1,650\text{ cm}^{-1}$ which is caused by the carbon-carbon double bond or vinyl functional groups (Figure 6). This absorption is present but very minor in the nujol prepared sample spectrum of standard MMA-TMPTMA in Figure 3, indicating that after polymerization the double bond character, as expected, is minimal. This confirms that a high degree of polymerization had been achieved.

A pyrolysis analysis of the MMA-TMPTMA Standard Bar was made to investigate the possibility of high temperature break-down products which could possibly accelerate chemical reaction with the cement paste, especially attacking and enhancing removal of the $\text{Ca}(\text{OH})_2$. IR spectra of pyrolysate (Figure 7) using both ATR (attenuated total reflectance) and gas cell transmission show increased absorption in the $1,600\text{--}1,650\text{ cm}^{-1}$ region. Since ample carbonyl absorption is also present, the reflectance spectrum in particular has, with some interpretive license, character of the acrylate and/or methacrylate families. There is, however, the possibility that the vinyl and carbonyl functions could exist on separate compounds in the condensate and/or gas pyrolysate mixture. Again, additional studies with the aid of possible chromatographic separation techniques would be necessary to resolve such questions.

SUMMARY AND CONCLUSIONS

Exposure of the two polymer impregnated systems, MMA-TMPTMA, styrene-TMPTMA, and control specimens in brine loop environments at 290° F for 1 year is accompanied by loss of crystallinity in the Ca(OH)_2 present in the concrete paste. Crystalline Ca(OH)_2 is still detected in styrene-TMPTMA concrete paste after 2 years but at significantly lower concentrations. Removal of both crystalline and amorphous forms of Ca(OH)_2 from the MMA-TMPTMA system specimens is suspected. There was no significant effect from either polymer system on the other normal mineral composition of the hardened cement paste.

The gross structural change to the MMA-TMPTMA polymer exposed to 290° F loop environments probably is a major factor in the disintegration and deterioration of this polymer concrete. What relationship the Ca(OH)_2 structural change has, if any, to the MMA-TMPTMA polymer and its performance is not known.

Since strict thermal degradation of the MMA-TMPTMA polymer does not begin until about 390° F, as indicated by DTA analyses, the additional environmental factors apparently combine to reduce the reaction temperature to somewhere between 250° F and 290° F.

The thermal degradation of the styrene-TMPTMA does not begin to occur until about 570° F which may account for its superior performance in the loops.

IR analyses of the polymer (MMA-TMPTMA) and its thermal breakdown products suggest, however, that thermal decomposition might provide methacrylate-like degradation products of low molecular weight. The probability of a reaction between any methacrylate compounds and calcium hydroxide in the concrete paste is suspected as the reaction of methyl methacrylate and calcium hydroxide has been demonstrated (2). The extraction of calcium hydroxide in crystalline and noncrystalline forms by another low molecular weight organic ester, ethyl acetoacetate, has also been reported (3). This extraction agent also attacks, though at a slower rate, the lime from calcium silicate hydrate in concrete tobermorite gel.

Any of these suspected calcium compounds formed from reactions with polymer degradation products are highly water soluble making them subject to leaching with consequent increase in the porosity of the concrete. Loss of calcium hydroxide also increases the hydrolysis potential of the calcium silicate hydrates.

We were unable to analyze for any of the suspected organo-calcium salts as no brine solutions from the specimen tests were provided. Additional studies are necessary involving the retention of all specimens and related materials in order to give a more complete analytical appraisal.

L. O. Trumbull Jr.

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1. Lenz, Robert W., "Organic Chemistry of Synthetic High Polymers," Interscience Publishers, 1967
2. Bureau of Reclamation memorandum, Applied Sciences Referral No. 72-3-1, Investigation of the Reaction Between Methyl Methacrylate and Calcium Hydroxide
3. Brunauer, S., "Tobermorite Gel - The Heart of Concrete," Am. Scientist, March 1962, Vol. 50, No. 1, pp. 210-229.

Enclosures

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Table 1

DETECTION AND IDENTIFICATION OF CALCIUM HYDROXIDE
AND CALCIUM CARBONATE IN CEMENT AND CONCRETE PASTES
BY XRD AND DTA

Specimen designation	Ca(OH) ₂		CaCO ₃	
	XRD	DTA	XRD	DTA
1. Cement, Type II (nonhydrated)	-	-	x (moderate)	-
2. Cement, Type II (hydrated)	x (high)	x	x (trace)	x
3. Concrete paste control 290° vapor, 1 yr	-	-	x (trace)	-
4. Concrete paste MMA-TMPTMA (not exposed)	x (moderate)	-	x (trace)	-
5. Concrete paste MMA-TMPTMA 290° brine 1 year	-	x	x (trace)	-
6. Concrete paste MMA-TMPTMA 250° vapor 1 year	x (moderate)	-	x (trace)	x
7. Concrete paste MMA-TMPTMA 290° vapor 1 year	-	x	x (trace)	x
8. Concrete paste styrene-TMPTMA 290° vapor 2 years	x (minor)	x	x (trace)	x

Present: x

Not detected: -

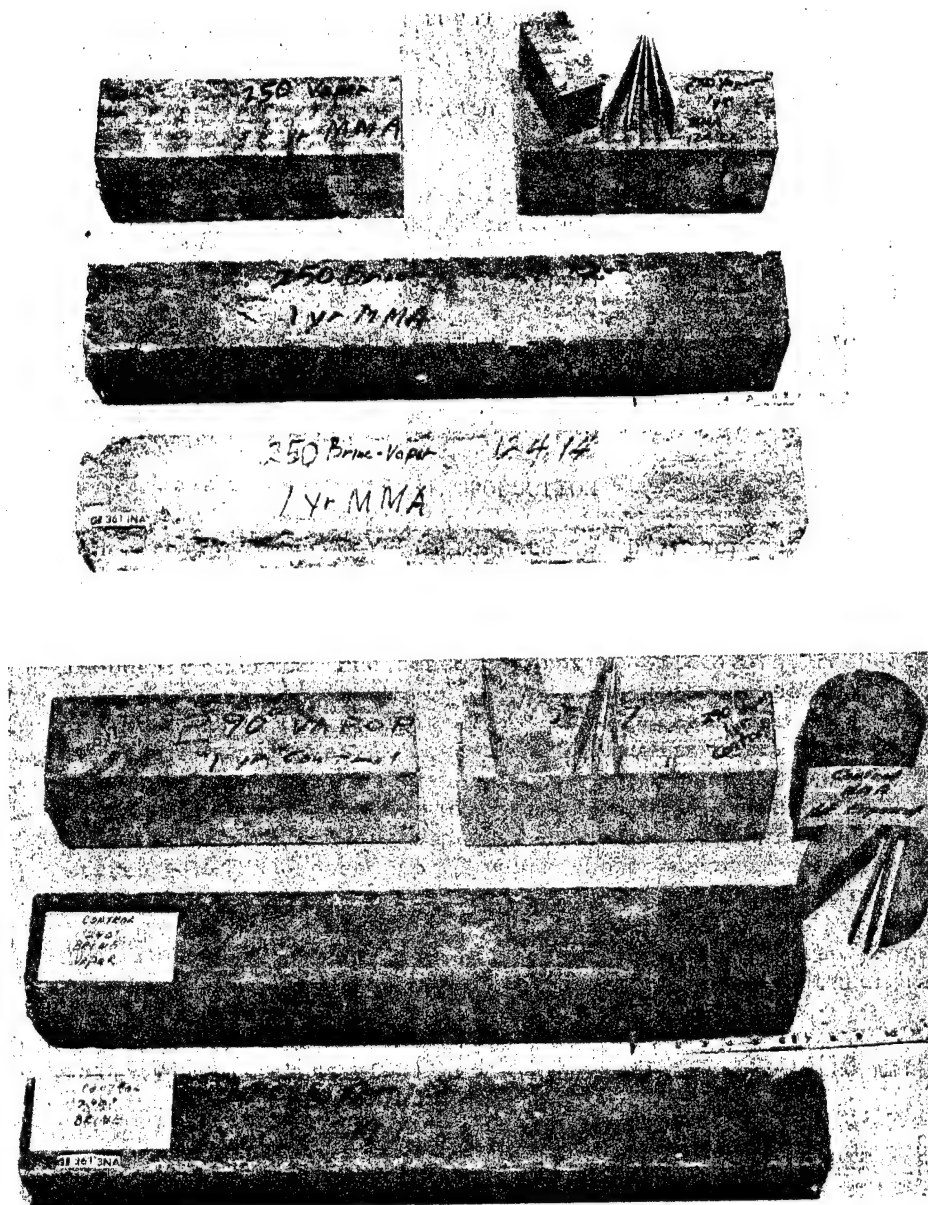


Figure 1A.—Photographs of Brine Loop Exposed Specimens*
 (Top) 250° F MMA-TMPTMA impregnated specimens essentially unaltered after exposure.
 Photo P801-D-77360
 (Bottom) Control or unimpregnated specimens after 290° F exposure essentially unaltered.
 *Unexposed control also shown. Photo P801-D-77361

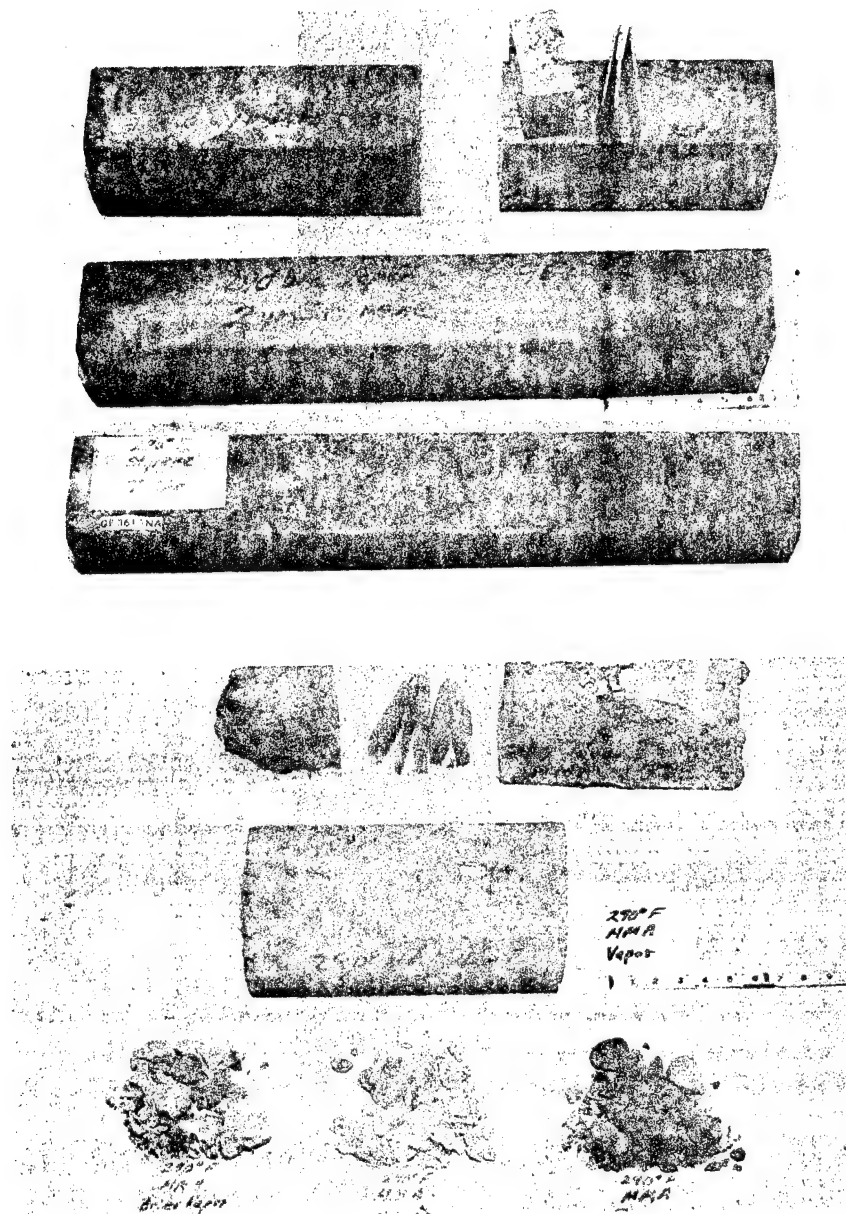


Figure 1B.--Photographs of Brine Loop Exposed Specimens

(Top) 290° F exposed styrene-TMPTMA specimens essentially unaltered after 2 years in brine loop.

Photo P801-D-77362

(Bottom) MMA-TMPTMA specimens show deterioration and disaggregation after 1 year exposure in brine loop.

Darker coloration of brine-immersed specimens result from iron-oxide deposit from loop container.

Photo P801-D-77363

Figure 2(A) X-ray Diffraction Patterns for Ca(OH)_2 and CaCO_3
Detection in Concrete Pastes

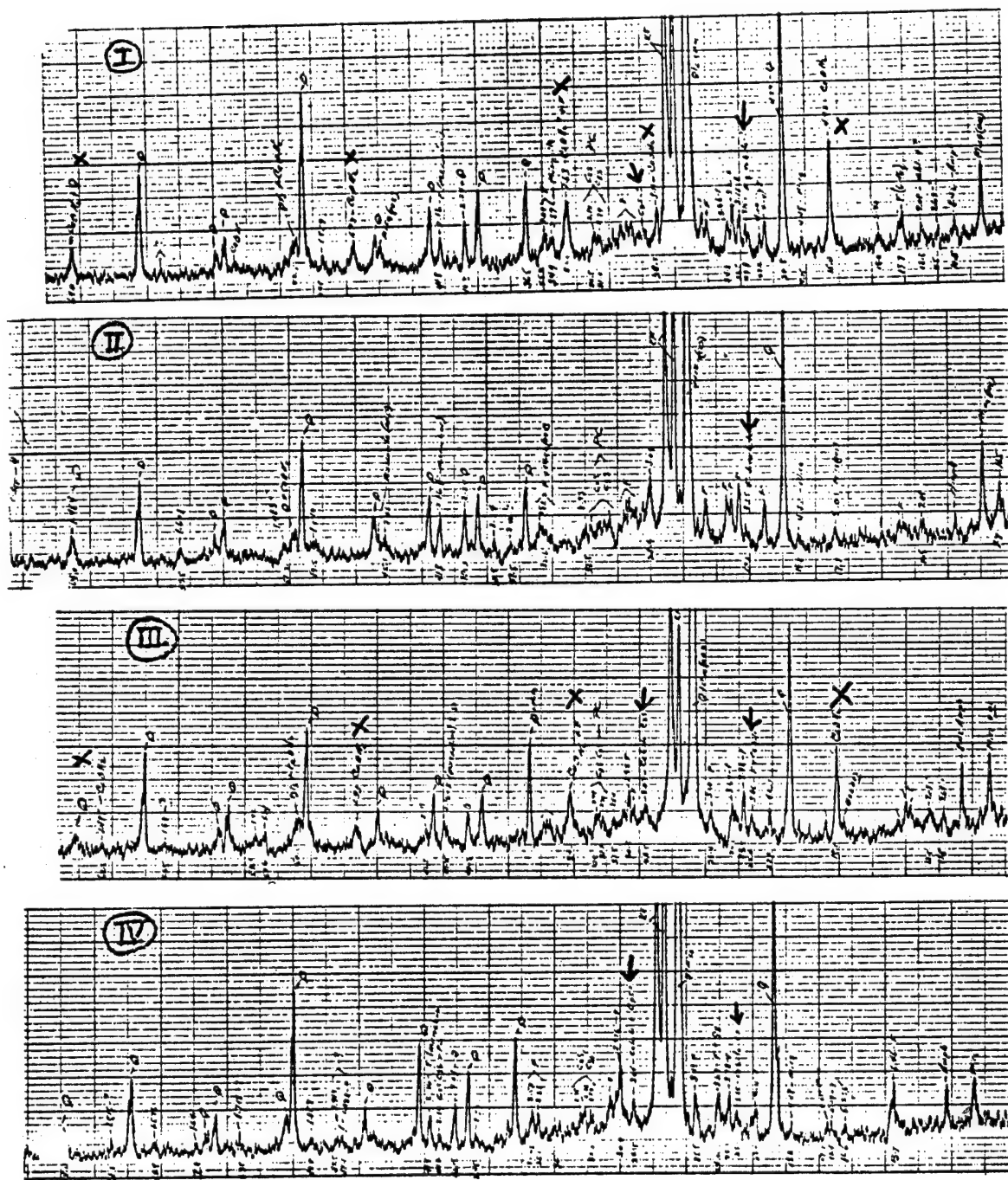
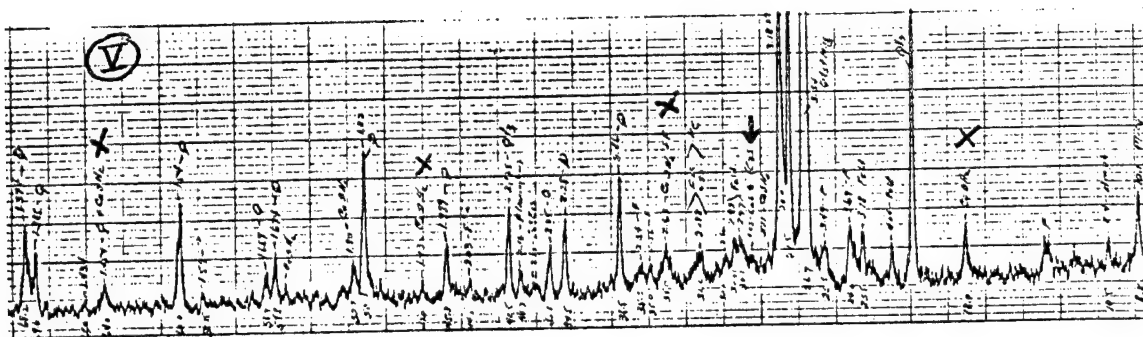


Figure 2(A) - continued



Note: X denotes Ca(OH)_2 peaks; ↓ denotes CaCO_3 peaks.

Pattern I was run from the paste of specimen No. 4, Table 1; MMA-TMPTMA impregnated, not exposed.

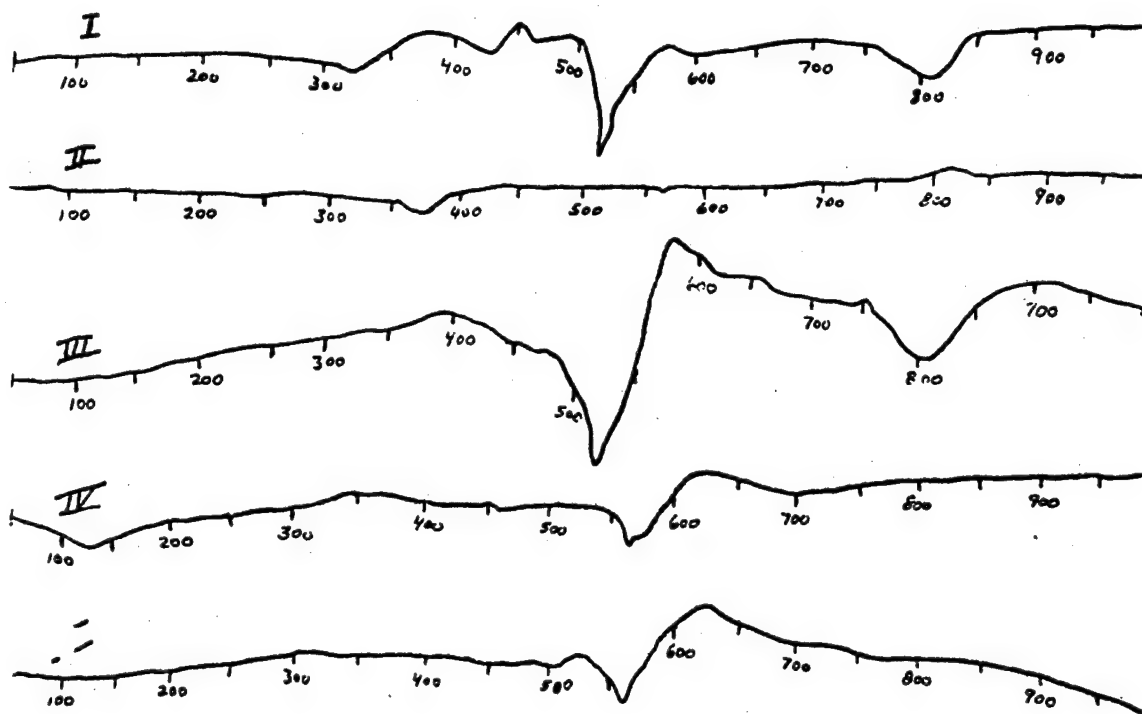
Pattern II represents Specimen No. 3, Table 1; control, 290° F vapor exposed for 1 year.

Pattern III represents Specimen No. 6, Table 1; MMA-TMPTMA impregnated and exposed to 250° F vapor for 1 year.

Pattern IV represents Specimen No. 5, Table 1; MMA-TMPTMA impregnated and exposed to 290° F brine for 1 year.

Pattern V represents Specimen No. 8, Table 1; styrene-TMPTMA impregnated and exposed to 290° F vapor for 2 years.

Figure 2(B). DTA Patterns for Ca(OH)_2 and CaCO_3
Detection in Concrete Pastes



Patterns presented in Figure 2(B) correspond with specimens analyzed by XRD (Figure 2(A)) and the order of presentation is also the same.

<u>Analytical conditions</u>	<u>Sensitivity (%)</u>	<u>Rate (°C/minute)</u>
I - Specimen 4	25	10° C
II - Specimen 3	10	10° C
III - Specimen 6	25	10° C
IV - Specimen 5	10	10° C
V - Specimen 8	10	10° C

Figure 3. Infrared Spectra of MMA-TMPTMA Polymer and Polymer Fragments

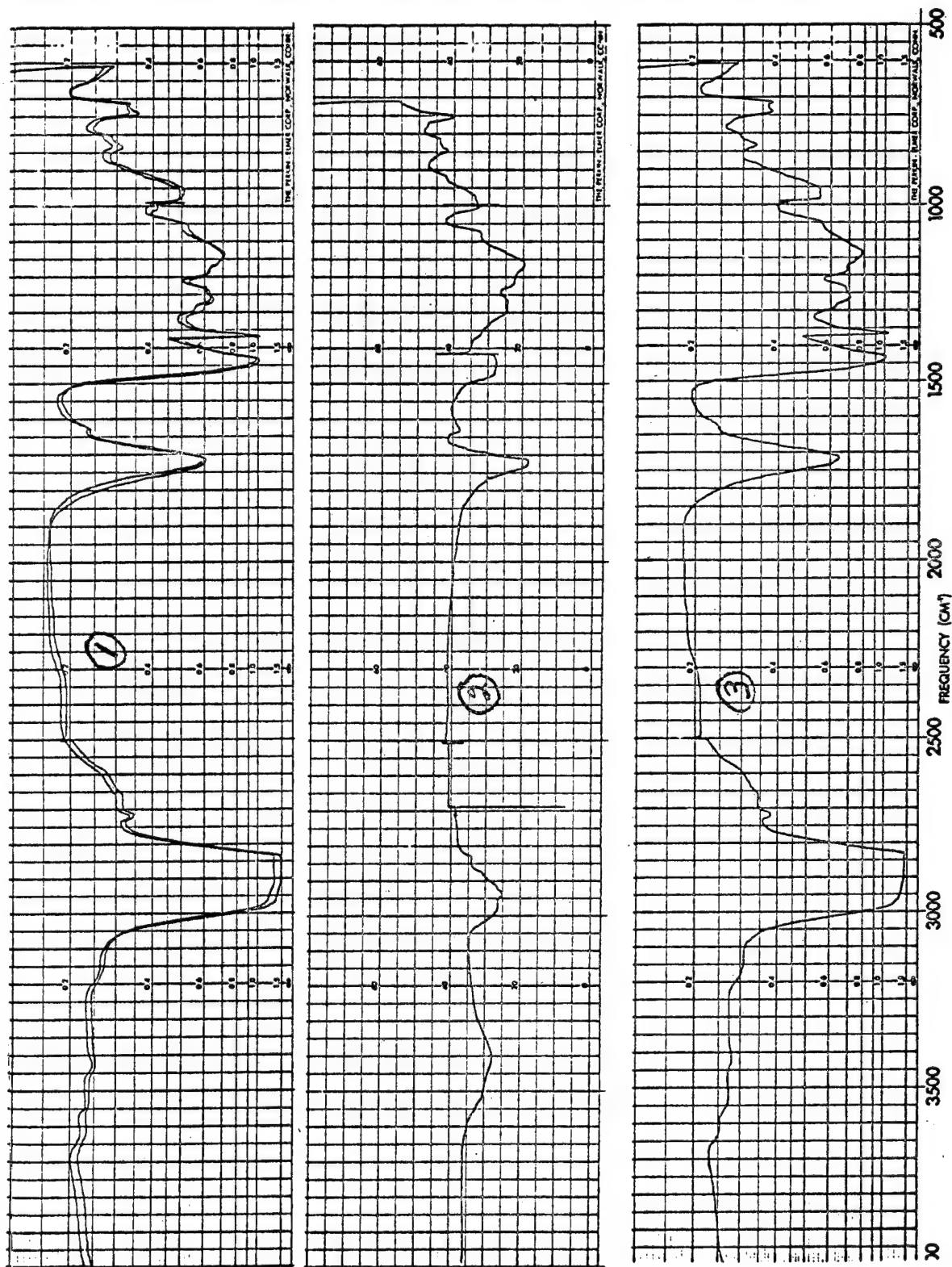
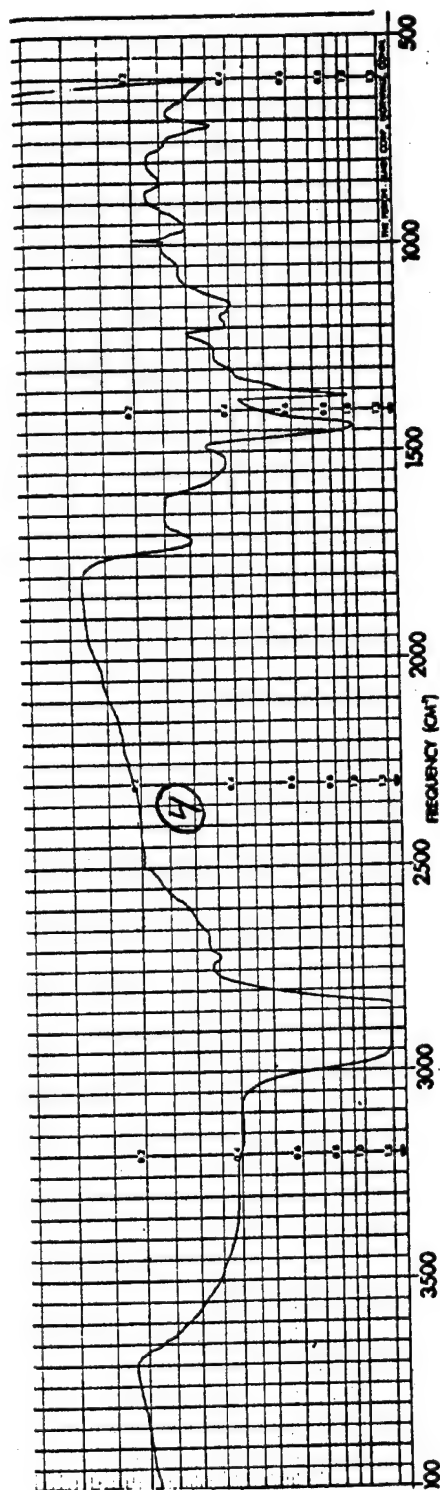


Figure 3. - continued



Spectrum 1 is of standard polymer bar powder suspended in nujol (mineral oil). Intense peaks near 3,000 and 1,500 cm^{-1} are caused by Nujol C-H absorption. Residual carbon-carbon double bond character is noted by weak peak between 1,600 and 1,650 cm^{-1} .

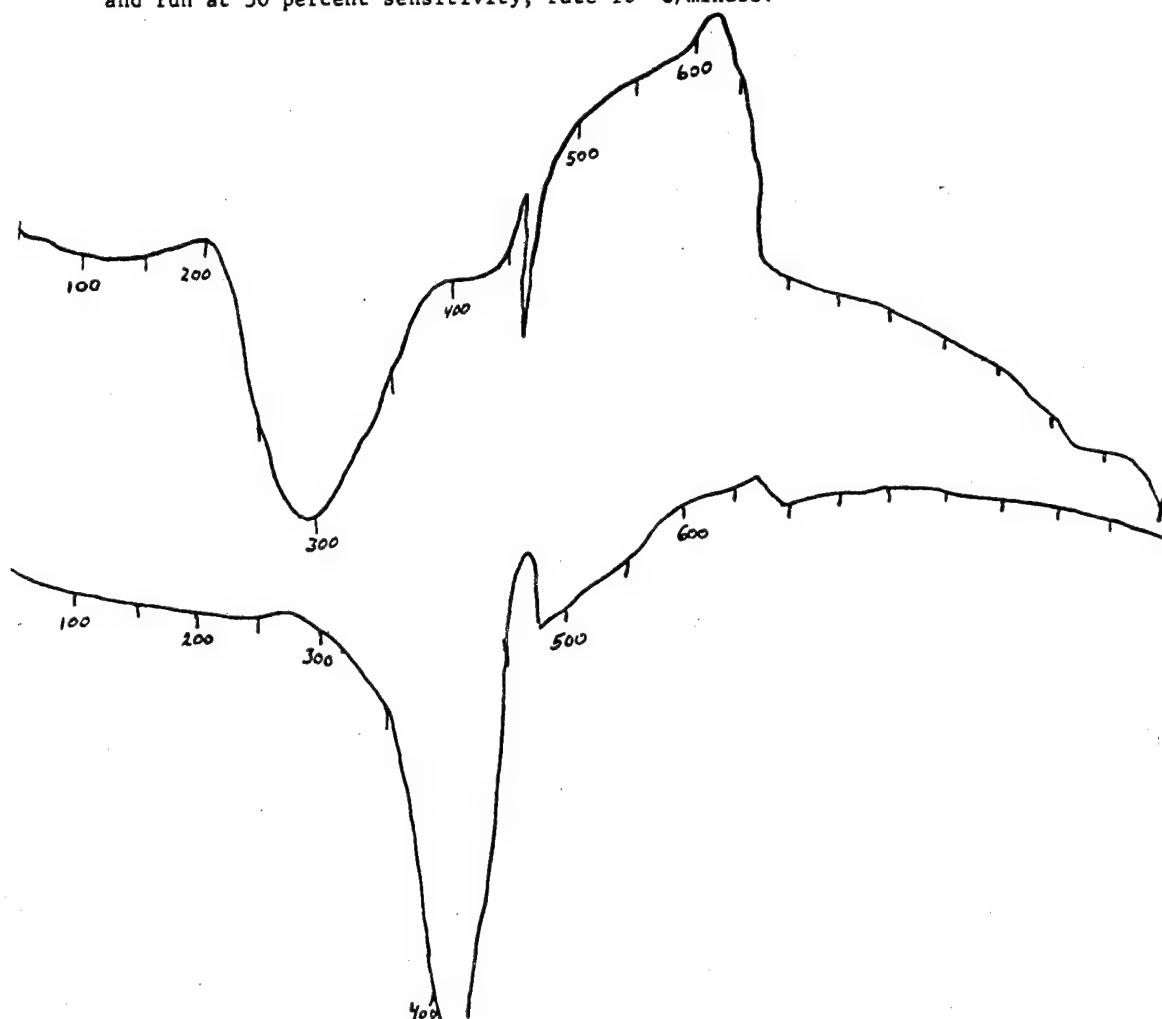
Spectrum 2 is of the same polymer bar powder pressed into a KBr pellet. Increased absorption near 3,500 cm^{-1} is caused by KBr absorption of water vapor.

Spectrum 3 is nujol mull preparation of MMA-TMPTMA polymer fragment from 250° F vapor 1-year exposure. Note similarity to Spectra 1 and 2.

Spectrum 4 is of a nujol preparation of polymer fragments from 290° F brine exposed specimens. Note substantial hydroxyl character (between 3,000 and 3,500 cm^{-1}) and other spectral differences from Spectra 1, 2, and 3.

Figure 4. DTA Patterns of MMA-TMPTMA Standard
Polymer Bar and 290° F Exposed Styrene-TMPTMA Fragments

MMA-TMPTMA standard bar powder - combined with 1/2 by weight inert material
and run at 50 percent sensitivity, rate 10° C/minute.



Styrene-TMPTMA polymer fragments powder - run at 25 percent sensitivity,
rate 10° C/minute.

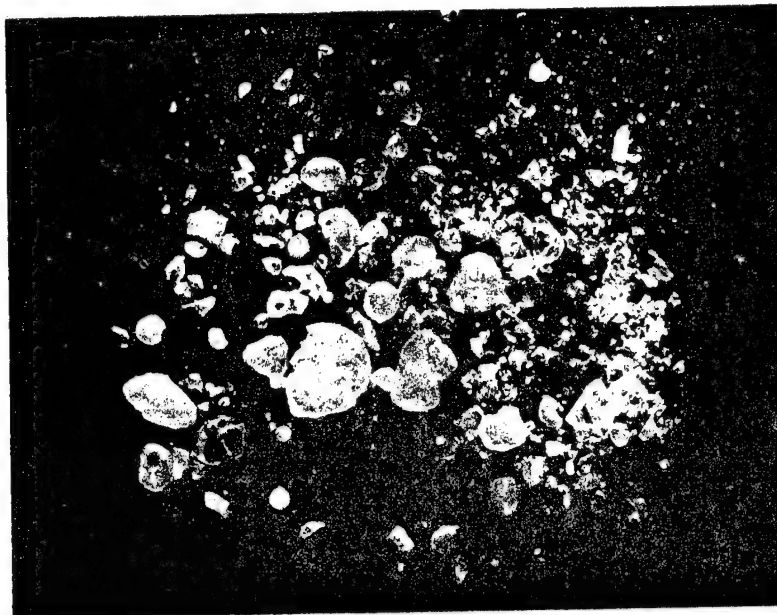


Figure 5A.—Photographs of Polymer Fragments Dislodged from Concrete Voids
 (Top) MMA-TMPTMA fragments from nonexposed specimen. Photo P801-D-77364
 (Bottom) MMA-TMPTMA fragments from 250°F vapor specimen exposure. These fragments show no obvious alteration from exposure. Photo P801-D-77365

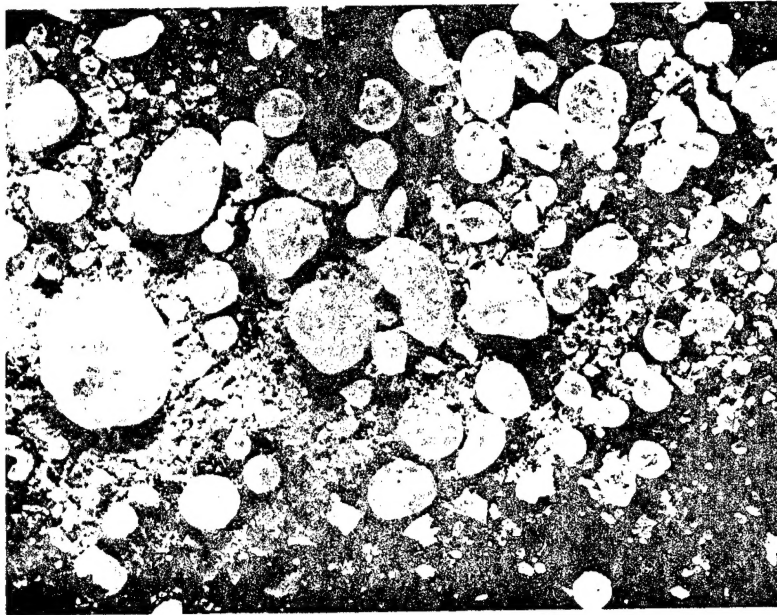


Figure 5B.—Photographs of Polymer Fragments Dislodged from Concrete Voids
(Top) 290° F vapor exposed MMA-TMPTMA specimen fragments. They show cracks from exposure. Photo P801-D-77366
(Bottom) 290° F vapor exposed styrene-TMPTMA specimen fragments. They show no obvious alteration from exposure. Photo P801-D-77367

Figure 6. Infrared Spectra of MMA and TMPTMA Monomers

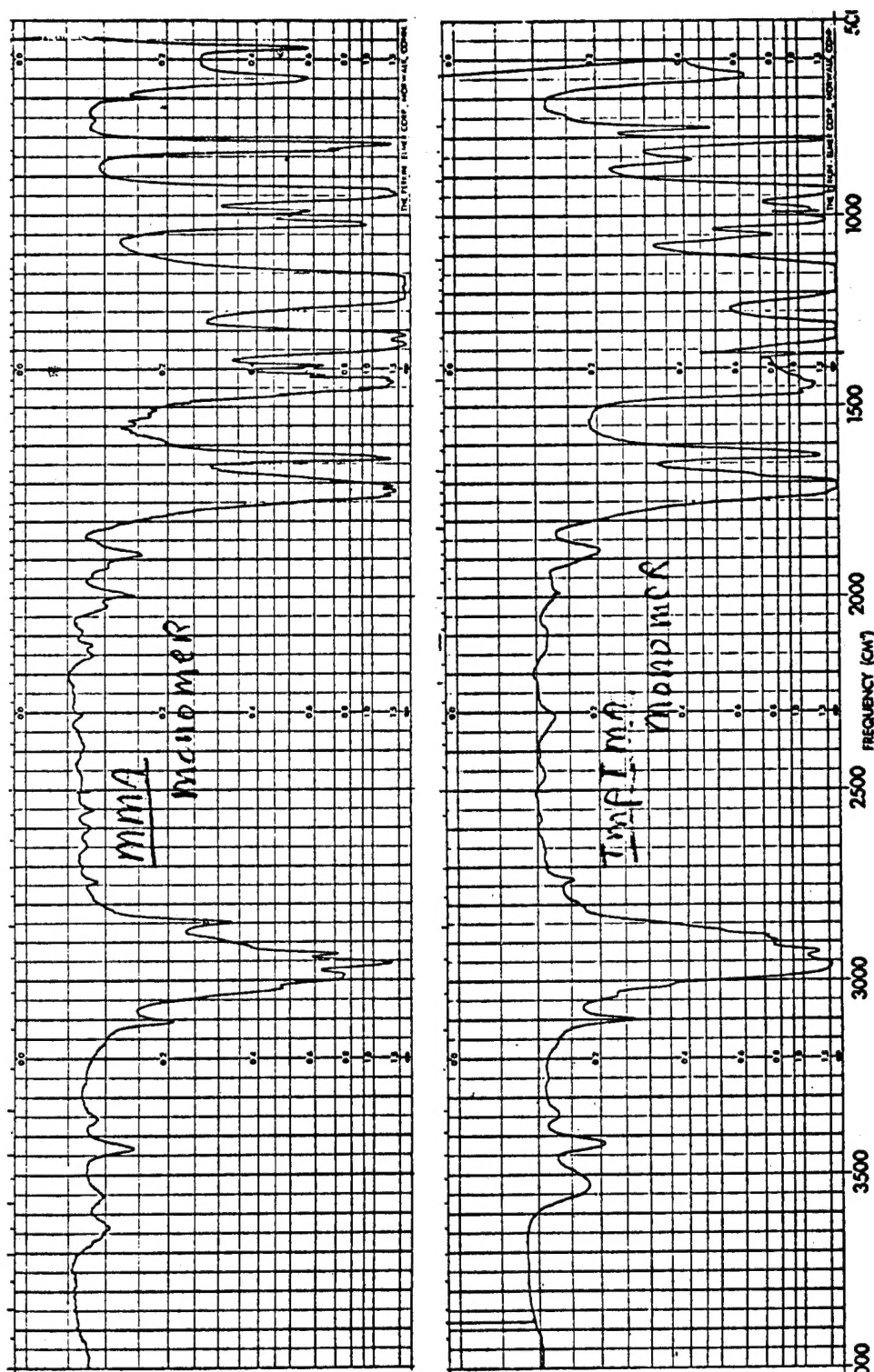


Figure 7. Infrared Spectra of Standard MMA-TMPTMA Polymer Bar Pyrolysates

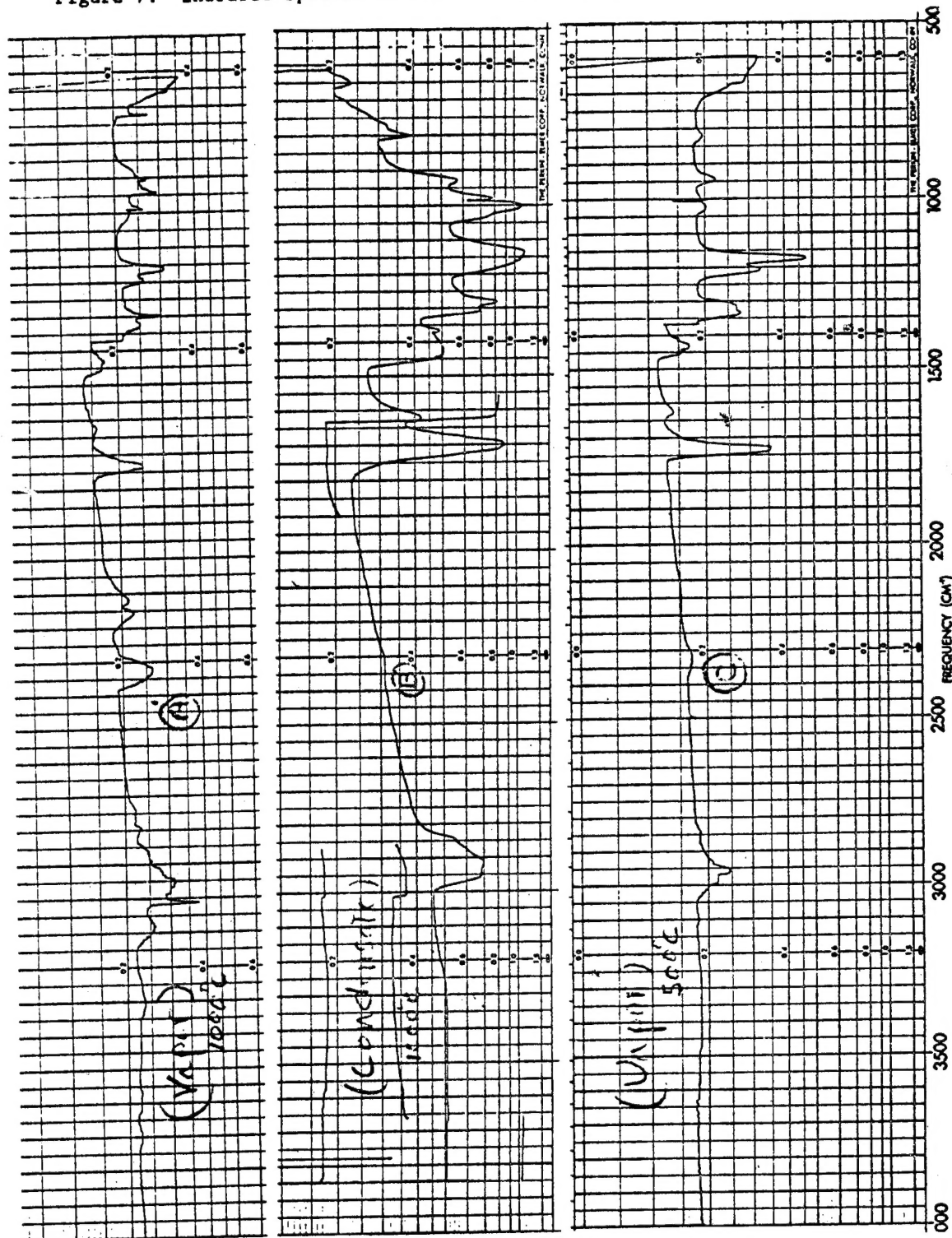
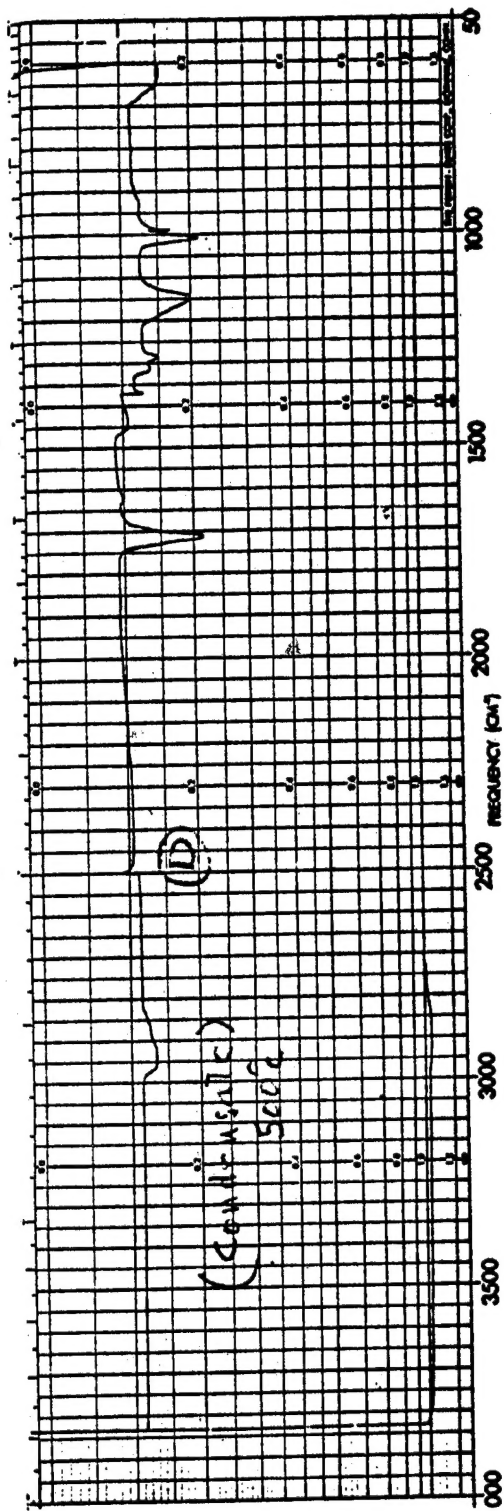


Figure 7. - continued



Spectrum A was obtained from the vapor of a sample pyrolyzed at 1000° C. Spectrum B was recorded on the condensate from the same pyrolysis by Attenuated Total Reflectance (ATR).

Spectrum C was obtained from the vapor of a sample pyrolyzed at 500° C. Spectrum D was recorded on the condensate by IR transmittance.

Although Spectrum A has more low molecular weight gaseous character as compared with Spectrum C, this is to be expected considering the difference in pyrolysis temperatures. All of the spectra, however, denote carbon-carbon double bond character and retention of carbonyl groups which is consistent with Methacrylate monomer character.